VIRTUAL AND RAPID PROTOTYPING
OF
FOOTWEAR COMPONENTS

by
Sandeep Kumar

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

MAY, 1999

VIRTUAL AND RAPID PROTOTYPING OF FOOTWEAR COMPONENTS

A Thesis Submitted in
Partial Fulfillment of the Requirements
for the degree of

MASTER OF TECHNOLOGY

by

SANDEEP KUMAR

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
MAY 1999

CERTIFICATE

It is certified that the work contained in the thesis entitled **"VIRTUAL AND RAPID PROTOTYPING OF FOOTWEAR COMPONENTS"**, by **Mr. Sandeep Kumar**, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

3/5/99

(Prof. S. G. Dhande)
Dept. of Mechanical Engineering
Indian Institute of Technology
Kanpur 208 016

May 99

Dedicated

To

My Father

Late Shri G. R. Gupta

ACKNOWLEDGEMENTS

I owe a deep debt of gratitude, respect and love to Dhande Sir, whose guidance, encouragement and fruitful discussions made me accomplish this work successfully. He is more than a Professor to me – he is a teacher who taught me to understand knowledge in its correct perspective. I enjoyed the care and affection he showered on me. I am thankful to him for giving me the opportunity to work with the leading end technologies like CAD, VP, RP & RT. Working close to the industry and in an open work environment under the able leadership of Dr. Dhande was a very fruitful learning experience. During the entire work he allowed me to work at my leisure. I learnt many things from him – dedication, discipline, hard work, and a practical attitude towards life. Working under him is a memorable experience for me.

I am very thankful to Super Tannery, Kanpur for providing an opportunity to establish interface from CAD, VP, RP, and RT to footwear industry.

Sincere thanks and regards to Bhattji, Puneetji, for the technical as well as personal discussions I had with them; their motivation and advice. They were there to resolve whenever I had a trouble, either personal or technical. Thanks to Sanatji for his kindness and support.

God was so gracious to give admission in IITK in the 97-summer batch. I had a great company during this period that made my life more enjoyful than other time. Especially Amreesh and Asit, who always came forward to solve misunderstanding among others and I. My sincere thanks to Dhish, Neeraj, Nema, for their throughout supports, amity, encouragement. I will always remember the dinner party at dhaba with them. I have a deep love in my heart for Bansal, Siddarth, Rahul, and Siva.

I sincerely appreciate the co-operation of CAD-P lab staff, during the course of my works.

Gupta.

SANDEEP GUPTA

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

F	Number of faces
E	Number of edges
V	Number of vertices
L	Number of loops
B	Number of bodies
G	Number of genuses
r	Curve radius
r_0	Standard radius
α	Angle control value
K	Global stiffness matrix
Δ	Displacement vector
F	Global right side vector
$\mathrm{E_c}$	Tensile modulus of composite
$\mathrm{E_m}$	Tensile modulus of matrix
$\mathrm{E_p}$	Tensile modulus of particle
$\mathrm{V_m}$	Volume fraction of matrix
$\mathrm{V_p}$	Volume fraction of particle

ABSTRACT

The present work is an effort to develop the methodology Virtual & Rapid prototyping, and Rapid tooling for footwear industry. Virtual prototyping consists of solid modeling of a component and its mold, FE analysis for the mold and generation of machining data for the mold. Rapid prototyping consists of creating STL and slice-formatted files of the component (shoe sole) and making a physical model using a RP system. Raid tooling consists of creating a physical mold in a suitable material. The role of epoxy tooling and metal spray coating for creation a mold has been evaluated in the present work. Using the spray coating along with epoxy tooling, experiments of making epoxy molds, with and without filler material have been carried out. Using the computational approach it has been found that the epoxy mold with filler material is comparable with gunmetal mold, in properties like induced deflection, stresses etc. The filler materials such as steel or aluminum granules are effective in increasing the strength of the mold as well as enhancing the heat transfer rate. By experiments as well as by simulation, it has been found that the application of a metal spray on an epoxy mold not only improves the quality of mold but also provides other operational benefits such as increased heat transfer rate etc. Epoxy molds have been found better than gunmetal mold in terms of cost, time, accuracy, skilled manpower etc.

Chapter 1

INTRODUCTION

1.1 PRODUCT LIFE CYCLE

Human needs often represent a powerful stimulus for new products. The required decision, responsible for the smooth and economic function of an existing product, the development of a new one, and at times its termination where there is no longer a need for product, are affected by the stages in the life cycle of a product.

The product life cycle (PLC) begins with customer's need and market demands from ideation to the finished product. The product goes through two main processes, the design process and the manufacturing process. The design consists of two main sub- processes, synthesis and analysis. Both are equally crucial to designer. During synthesis, the philosophy, functionality and uniqueness of the product are determined. The end goal of the synthesis is a conceptual design of the prospective product.

The other main sub-process, analysis, begins with evaluation of the performance of the expected product. This constitutes design modeling and simulation. The quality of the results and decisions involved in the activities to follow such as design analysis, optimization, and evaluation is directly related to and limited by the quality of the chosen design model.

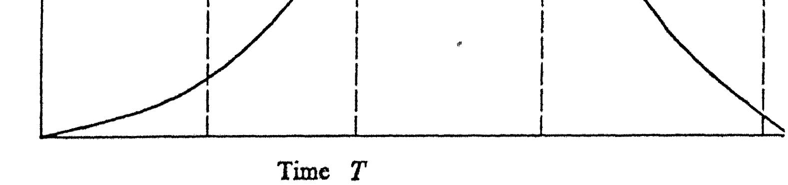


Fig 1.1: Phases in the life cycle of a new product

The phases in the life cycle of a product are described by the following four stages, which are shown in the figure 1.1[Richard77]:

(i) Infancy

After a product is introduced, it goes through an infancy stage, characterized by the presence of many risks and a high mortality. The numerous failures of new products are related to unforeseen product weaknesses, market conditions, or other factors beyond management's control. Demand growth in this phase is slow and can be attributed to the group of consumers willing to experiment with an unproved item.

(ii) Growth

For a new product that survives the infancy diseases, there follows a period of rapid demand growth. Acceptance is now gained among wider segments of the market, through wider recognition of a need being satisfied more effectively or more economically. The importance of an accurate demand forecast in this phase is crucial. Undue optimism may result in unwarranted heavy investments. The resulting high production cost per unit diminishes as the firm's ability to compete and create a lack of funds elsewhere. Similarly, excessive pessimism may prevent an organization from taking advantage of market opportunities and establishing a strong market position.

(iii) Maturity

Once demand reaches a saturation level, a product has entered the phase of maturity. At this stage, the demand is related to replacements and population growth. Products that satisfy genuine needs remain in the maturity phase for long times, e.g. food items, soap, books, TV sets etc. Items directed at satisfying psychological wants, however, have a rather ephemeral existence, e.g. fashionable cloth, interior-decorating items, movies, hit records, and others.

(iv) Decline

After a time in the maturity phase, a product may enter a phase of decline. The introduction of new improved substitutes, changes in technology, changes in the economy, or other considerations bring about a drop in demand until it is no longer economical to produce the item. The introduction of pocket calculators made slide rules obsolete. Color TV sets replaced Black & White ones by covering the same need

better. The increasing cost of energy is making people switch to smaller, more fuel-efficient automobiles.

Producing and marketing a product must be changed in each phase to achieve an optimum utilization of capacity for existing market conditions. For an on-going concern new products must be prepared, as current products approach the decline phase. Otherwise, declining demand results in poor utilization of available productive capacity, with potentially disastrous efforts to the organization's financial health. Ideally, new products must be introduced so that their infancy phase coincides with the end of the maturity phase for existing ones, figure 1.2 [Richard79].

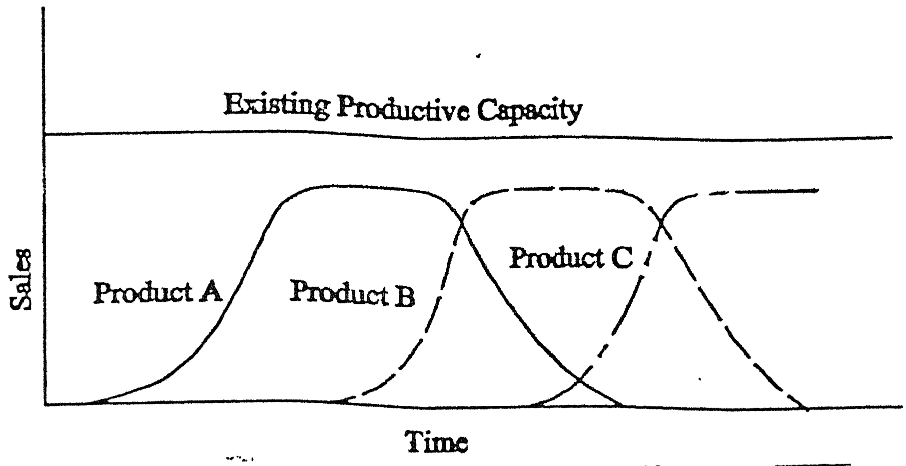


Fig 1.2: Phasing in new products for optimum capacity utilization

The life cycles of some products show an initial peak, followed by a decline to a fairly stable level. The peak may reflect consumer trial, stimulated by aggressive marketing support. The decline may reflect the failure of some customers to repeat their purchases because they didn't find the new offering superior to their present one. The stable portion may reflect continued repeat purchases by that segment of the market to which the new product had lasting appeal.

The development of new products requires not only the skills to anticipate market trends and new technologies, but also the capability for timely use of internal or external R&D efforts. The objectives of R&D are directing formal concerted efforts toward creating new products, finding new uses for existing products, and developing new processes that will reduce capital on manufacturing costs.

The principal applications of PLC analysis occur in planning for new products and in changing marketing strategy for established product. Length of the PLC, the height of peak demand, and the general shape of the PLC curve, contribute special role in product design [Everett78].

1.2 VIRTUAL PROTOTYPING

Virtual Prototyping (VP) can be defined as visualizing and testing CAD models on a computer before they are physically created. Virtual prototyping is accomplished by running a computer model through iterative dynamic simulation before making a physical prototype.

A physical prototype can require a lot of manual tooling, skilled-hand assembly, dedicated testing and instrumentation. The interpretation of the data generated by prototype testing is time consuming. Engineers must incorporate what was learnt by revising the design and making new prototypes. The entire process has to be repeated several times. The time associated with all these processes can be days or weeks.

Virtual prototyping performs all the above steps on a computer, runs more variation than a physical prototyping system and permits the design tests not feasible in the laboratory. This versatility permits CAD model modification and refinement to be accomplished much more rapidly than with conventional design tests. Virtual prototyping, enhances solid modeling of prototype, leads to better visualization, evaluates physical parameters such as volume, areas etc; generate the interfacing file with prototyping hardware, create the die or mold virtually, performs analysis of flow as well as stress and deflection developed in mold & dies. Further extension of this concept is called virtual reality, where the individual is immersed in the virtual world, interacting and feeling him as a part of the world. Such systems are of significant engineering use like flight simulation of an aircraft [Rao94].

1.3 RAPID PROTOTYPING

The term Rapid Prototyping (RP) refers to a group of new technologies, which produce models or prototypes of a simple or complex part from 3-D CAD model files without using conventional tools or fixtures. In a RP system, a prototype is rapidly obtained by hardening photosensitive polymer or sintering powders using curing media like lasers, heating elements etc. The four basic steps involved in creating a model in any RP systems are as follows: (i) creation of a CAD model, (ii) creation of STL file, (iii) slicing of the model, and (iv) building up of the part. The process of triangulation and slicing determine the geometry accuracy of the part. The number of slices should be optimized to achieve a trade-off between using time and surface quality. The part orientation, while slicing, should ensure a stable and stress-free part in all stages of construction. The part orientation should also facilitate easy clean up operation.

The following is a list of commonly used RP processes [Yan96]:

- Stereolithography,
- Fused Deposition Modeling,
- Laminated Object Manufacturing,
- Selective Laser Sintering,
- Solid Ground Curing,
- Three Dimensional Printing,
- Ballistic Particle manufacturing.

In these processes, we have following two processes in CAD-P laboratory, Mechanical Engineering department, IIT Kanpur.

1.3.1 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is the name of the technology used by commercial RP system from Stratasys Inc. (Minneapolis, MN). The Stratasys systems are primarily targeted for the engineering office environment for use during the conceptual design stage of product development. Simple operation, inert materials and lack of fumes make the FDM process quite compatible with an office environment. In this process, a model is built using a thin filament of thermoplastic polymer namely ABS (Acrylonitrile Butadiene Styrene). The filament is heated and passed through a nozzle. The movement of the nozzle forms a layer, which is allowed to be solidified in

the closed cabinet at 70°C, which takes a few seconds. For overhanging features, a separate nozzle head deposits the support material. The process is shown in figure 1.3. Once the model is built, the support material can be easily broken off from the part. This process is inherently slow during layer deposition. However, no post curing is required in this process. Compared to other processes, FDM has relatively lower initial cost and easy operation. The running cost is also low. The surface in this case may need some finishing operations.

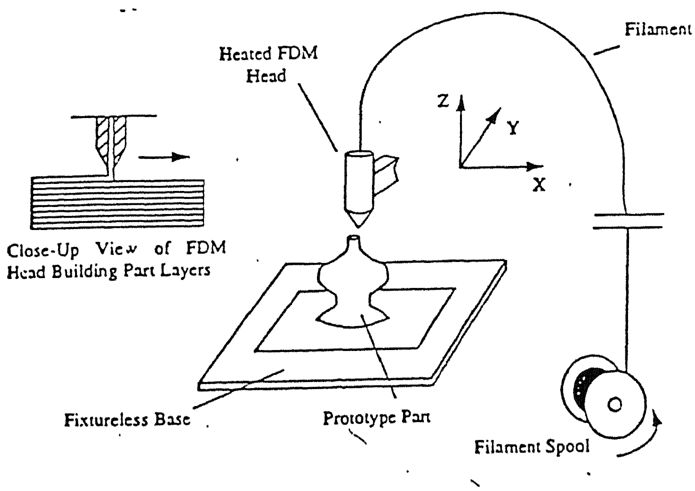


Fig 1.3: The Fused Deposition Modeling Process

The basic input for any rapid prototyping process is an STL (STerioLithography) file that is obtained from a CAD model. The geometric modeling of the objects in computer aided design can be done using three methods viz., wireframe modeling, solid modeling and surface modeling. The wireframe modeling approach is not appropriate for STL creation, as it does not have the volumetric data. Solid modeling is very useful in the creation of volumetric object and hence helpful for STL creation. The solid modeling package, I-DEAS (of SDRC Inc., USA) is used in the present work. I-DEAS is based on the variational technology that means that one can do any operations on the model without specifying the dimensions in the initial stages. This variational technology could prove helpful in conceptual design wherein one can proceed with the ideas in his mind without any dimensions. At any stage the model can be edited for adding the dimensions and all the operations done on the model will be updated immediately.

- **Solid Ground Curing**

Cubital Limited, Israel has developed a RP system based on a technology called Solid Ground Curing (SGC). This system is called Solider. In this process, a layer of liquid polymer resin is cured by ultraviolet light. This is accomplished by exposing the layer in a flash or flood manner. The boundary and area for exposure is generated by developing a glass mask plate by electrostatic deposition of black toner powder outside the boundary. All voids in a layer are filled with wax followed by milling to provide a flat support of exact height for the next layer. When all layers are complete, the prototype part is washed away to remove the water-soluble wax. Cubital photopolymer resin is completed cured during fabrication of each layer. No post curing is required. The process is shown in figure 1.4.

The Solider system builds as many prototypes, in a given run, as can be positioned within its work volume. An option exists for flexible definition of work envelope so that a reduced volume can be used for few or smaller parts. The Solider system has the ability to build working assemblies, such as interlocking gears or a bearing, directly from the assembly CAD data.

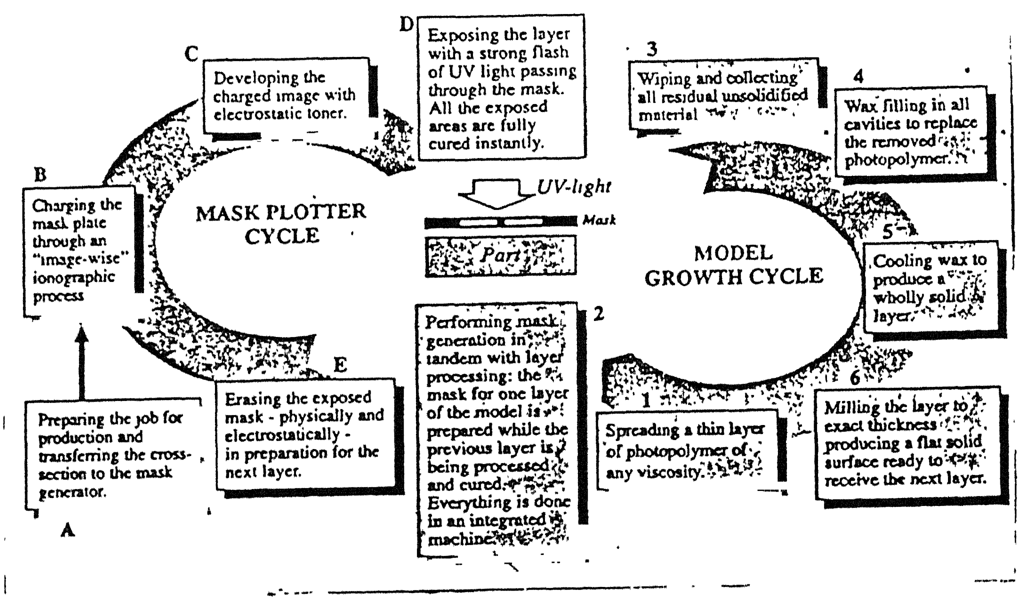


Fig 1.4: The Solid Ground Curing Process

The SGC process provides high dimensional accuracy and surface finish. However, the machine is bulky and has a large number of moving parts. The installation, operation, and maintenance costs are high.

1.4 RAPID TOOLING

Although RP is introduced as a designer's visualization tool, the cost involved does not justify its usage restricted to visualization alone Therefore efforts have been made to further the use of the RP part to manufacture the tools. A tremendous pressure on compressing the led-time to develop new products as a major bottleneck in many sectors, especially those in which product shapes are complex (such as automobile and consumer products). Several developments occurring simultaneously have suddenly focused attention on rapid development of tooling for the casting, molding and sheet forming industries. The main idea is to get a tool that can yield few hundred or thousand components using RP as master pattern. This opened up a new field called *Rapid Tooling* (RT).

There are several ways in which the tools can be manufactured rapidly. These are classified into the following two major group's.

a) Indirect RT processes

In these processes, the starting point is the RP component for which the tools are to be manufactured. The MCP TAFA process is an indirect RT process, in that it needs the pattern, which is made on a RP machine. Others RT processes in this category are MCP Vacuum Casting process and MCP Low melting Alloy process.

b) Direct RT Processes

In these processes the tools are directly manufactured in layers. From the CAD data available, the mold can be designed for a particular component and the resulting mold can be made by any RP process. Direct RT processes are Direct Metal Laser Sintering, Laminated Laser Cut Cavities etc.

The recent developments in the rapid prototyping technology and the availability of newer materials have acted as catalysts in opening up new routes to tooling production. Most widely used materials for producing rapid tooling include thermosetting polymers: epoxy resins, polyurethane, and silicones. Metals, especially those with low melting point are also used in some processes. Using computer aided design, electronic data transfer, process simulation, and RT technologies, tooling costs and development times can be reduced by as much as 75 percent or more. By reducing

tooling costs, RT enables high volume processes, such as injection molding, to be completed at lower production volumes.

RT can be used in many manufacturing processes. For plastic parts, RT can be used in conjunction with following manufacturing processes: injection and compression molding, vacuum casting, vacuum forming, glass reinforced plastic lay-up, blow molding, extrusion etc. For metallic parts, RT can be used in conjunction with following manufacturing processes: sand casting (patterns, matchplates, coreboxes), investment casting using wax patterns, sheet metal forming, die casting, hot and cold forging etc. For ceramic parts, RT can be used in conjunction with slip casting, isostating forming, and powder compaction in presses [Bapat98].

Generally, most RT applications have involved soft tooling. Materials with lower hardness are considered 'soft', e.g. silicones, rubber, epoxies, low melting point alloys, zinc alloys, aluminum etc. But soft tools are used for small-lot size production. There is a gradual shift to hard tooling. Hard tooling is often referred to that made from hardened tool steel.

Choice of the process depends on the master pattern. If it is relatively small, the vacuum casting could be a better choice. Expected life of the mold will also control the choice of process. At present following is popular RT systems available:

- MCP TAFA ARC SPRAY SYSTEM

  This is meant for producing injection molds, blow molds, and vacuum forming dies. Here size is not a limitation.

- MCP LOW MELTING ALLOY SYSTEM

  This system is primarily used for making press tool dies.

- MCP VACUUM CASTING SYSTEM

  This is popular system for making silicone molds. This is a soft tooling process.

- QUICKCAST PROCESSES

  This process is a trademark of 3D systems and it produces patterns for Investment Casting.

1.5 OBJECTIVES OF PROPOSED WORK

In the present work an attempt is made to prepare injection molds of shoe-sole, by Epoxy molding with metal spray method. Main goal is to establish the process itself. One of the objectives is to prove the capabilities of RP&T to the footwear industry. RP pattern is made on different type of RP processes, available at CAD-P lab in I.I.T., Kanpur. Effect of different parameters on the performance of molds is studied. Different types of processes are developed to make the injection molds using RP part as pattern. These processes are to be evaluated both qualitatively as well as quantitatively. Quantitative evaluation has been done for strength analysis as well as life of the molds and dies. For strength analysis, FEM has been used as the approach of evaluation. To summarize the problem could be stated as:

- To establish processes for creation of molds of shoe-sole by RP process.
- To study different parameters on these processes both qualitatively as well as quantitatively as Virtual Prototyping.

1.6 LITERAURE REVIEW

In this section the previous work done in the field of Virtual Prototyping, Rapid Prototyping, and Rapid Tooling, relevant to present work is reviewed.

Yan and Gu [Yan96] have discussed several new and promising rapid prototyping-manufacturing techniques. The techniques are all based on material deposition by layer by layer technique. Each of them has particular features in terms of accuracy, material variety and the cost of the machine. They feel at great effort is needed for research and development of these technologies so that they can be widely used in product-oriented manufacturing industries.

Zheng, Lewis, and Gethin [Zheng96] have been introduced an alternative approach for Delaunay triangulation, in which the triangulation is mapped from an equivalent convex-hull of a higher dimension. In this equivalent convex-hull, all points are extreme points. This feature makes a special treatment possible so that the equivalent convex-hull algorithm has smaller complexity than the general procedure. They also considered various parameters involved in the point creation algorithm.

Boender, Willem, and Frits [Boender94] has been described an approach to automatic FE mesh generation from CSG representation of 3D solids with curved

faces. The paper is divided in to two parts. The first part is a boundary-evaluation procedure for a CSG model that uses an exact representation of the faces of the primitives. The second part is the derivation of a FE mesh from the B-rep resulting from the boundary evaluation. They describe that B-rep more suitable than CSG for FE mesh, since it is possible to position FE points exactly on the vertices and edges of the solid model, and to determine whether the elements intersect the boundary of the solid.

Floriani, Falcidieno, and Pienovi [Floriani85] have been discussed about the Delaunay triangulation algorithm for arbitrarily shaped regions, which is a method for building 2½ -dimensional representation of surfaces defined at points randomly distributed within domains of complex geometry. Their method is dynamic, since it works by stepwise inserting the internal points on a separately generated triangulation of the boundary. The algorithm can be combined with a point selection criterion.

The paper presented by Piegl and Tiller [Piegl98] describes an algorithm for obtaining a piecewise triangular approximation of a trimmed NURBS surface. It assumes only C^0 surfaces and processes the geometry based on the control net. The surface is subdivided into rectangular regions that are merged with trimming loops. The new regions are then triangulated independently to be merged into a triangulation of the entire trimmed domain. Both the triangulation and the subdivision part of the algorithm are very simple and efficient. The quality of the triangulation is exceptionally good, as the subdivision of the patch is geometry based.

Sheng and Hirsch [Sheng92] give a new approach for triangulating trimmed surfaces. The triangulation is performed completely in parametric space, so that the procedure runs fast and reliably. Using this algorithm it is also easy to prevent cracks between patches and surfaces. This makes the algorithm particularly suitable for the generation of a valid triangulation model for RP machines.

Dolenc and Makela [Dolenc94] give the overview of several procedures for generating the layer from a CAD model such that the resulting part can be accurately manufactured using layered manufacturing technique. Their main contributions are the development of methods for handling flat areas and the restriction of the staircase effect to a user-specified tolerance. In addition, they explain how offsetting the slice

computes by the intersection algorithm can account for post treatment operations, to minimize the number of layers, or to obtain a more accurate part.

Kulkarni and Dutta [Kulkarni96] have described two factors i.e. staircase effect, and containment problem, associated with the slicing procedures used in layered manufacturing processes that introduce geometric inaccuracy. This algorithm ensured that none of the tangential points on the surface are missed while slicing the object. This paper also gives the comparative study between adaptive slicing and uniform slicing.

The paper, presented by Sabourin, Houser and Bohn [Sabourin96] presents a new adaptive slicing method for layered manufacturing and its integration with commercial rapid prototyping software for Fused Deposition Modeling. This method improves on past work by partitioning the adaptive layer thickness refinements. The paper is also described the advantages of this method for adaptive slicing over uniform slicing.

1.7 ORGANIZATION OF THE THESIS

This thesis comprises of five chapters. It is organized in the following manner.

Chapter 1 gives a general overview of Product Life Cycle, Rapid Prototyping, Virtual Prototyping, and Rapid Tooling. Also it portraits the some process of RP i.e. Fused Deposition Modeling (FDM), and Solid Ground Curing (SGC).

Chapter 2 explains the procedure to create computer-aided solid modeling of a prototype-using solid modeling tool and processing of FDM process to create RP part, for making of molds.

Chapter 3 is consisting the virtually creation of molds as well as virtually quantitative evaluation of effect of different parameters on molds and dies through FE simulation (strength analysis).

Chapter 4 explains the different types of RT processes for making the physical molds using the RP pattern.

Chapter 5 concludes the report and suggests for improvement of methodology as well as future work.

Chapter 2

MODELING AND RAPID PROTOTYPING

2.1 INTRODUCION

In a competitive, increasingly global economic environment where high quality and fast time-to market are critical to a products success, engineering designers to artists were looking for a tool which can convert their thought and ideas regarding a product to a physical object. One promising set of emerging technologies is rapid prototyping, which allows physical part to be produced quickly from three-dimensional CAD data. Advancement in computer graphics added a new era in this field.

With rapid prototyping systems, engineers can build conceptual models and convey ideas more quickly and completely than with earlier methods. These systems can be used to build "quick-look" prototype for analyzing a part's form, fit and function. It can also be used as master pattern for developing rapid tool. Rapid prototyping can result in improved design quality, shorter design life cycles and lower development cost.

The basic steps involved in producing a prototype is same for various rapid prototyping processes, which can be explained briefly as follows [Kai96]:

i. Creation of fully closed surface or solid CAD model of a part to be manufactured, using any standard solid modeling software package.

ii. Conversion of CAD model into a file format that is acceptable by the RP system for pre-processing. The STL file format is the de-facto industry standard.

iii. Slicing of the STL file format of the part into layers of prescribed thickness in a prescribed orientation, by the control unit of the RP system.

iv. Processing of sliced model for editing can be done, if necessary.

v. Running the hardware for the creation of a physical 3D model.

vi. Postprocessing or finishing of product can be done by removing of support material and cleaned.

The whole process is described in three steps as follows.

2.2 PREPROCESSING

The preprocessing involves all the steps which are used by the software of the RP machine i.e. creation of CAD model, creation of STL file format. These steps are described in detail.

2.2.1 Geometric Modeling

Geometric modeling refers to a collection of methods used to define the shapes and other geometric characteristics of an object. The methods of geometric modeling are a synthesis of techniques from many fields such as analytic and descriptive geometry, topology, set theory, numerical analysis, vector calculus, and matrix methods. For geometric modeling of an object in CAD, one can use three different modeling methods. These are (i) wireframe modeling, (ii) surface modeling, and (iii) solid modeling [Bhatt97].

The wireframe modeling approach is adequate only for drafting purpose. The surface modeling method allows a design to define complex, free form surfaces. However, both these methods do not provide volumetric information of objects. Solid modeling is suitable for modeling and designing volumetric objects.

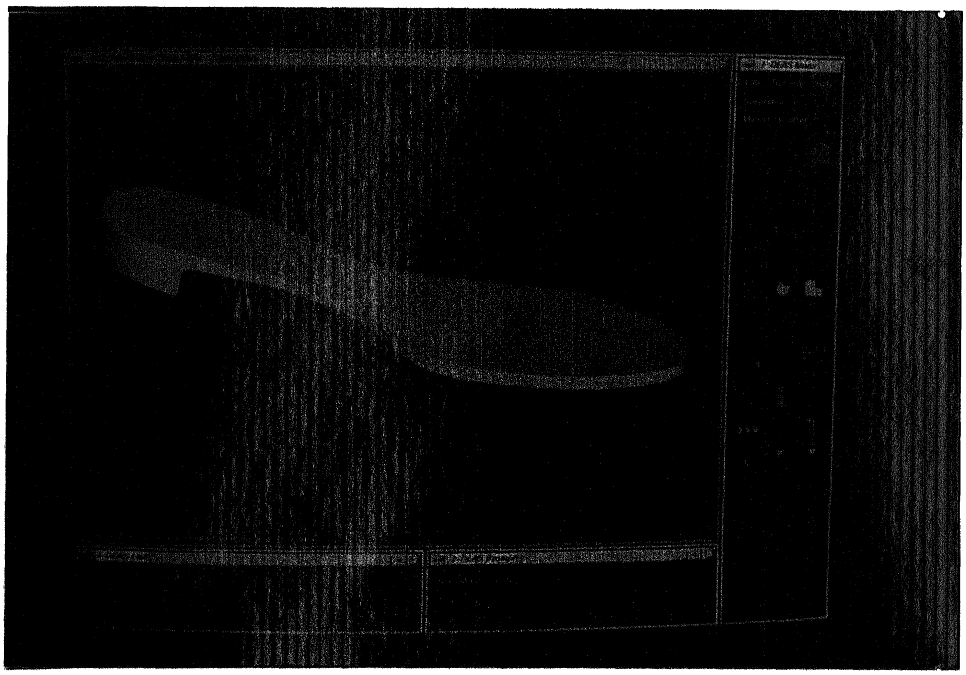


Fig 2.1: Solid model of shoe sole

A solid model should provide the following mathematical characteristics, such as rigidity, 3-D homogeneity, finiteness and finite describability, closure under rigid motion, closure under regularized Boolean operation, and boundary determinism. The mathematical implication of the above properties suggests that valid solid models are bound, closed, regular, and semi-analytic subsets of a 3-D Euclidean space. A solid model for shoe sole is shown in figure 2.1. For any solid modeler, the underlying schemes of data representation such as boundary representation, constructive solid geometry, spatial occupancy enumeration etc. is a crucial feature. For a simple solid object as shown in figure 2.2, following two schemes are described.

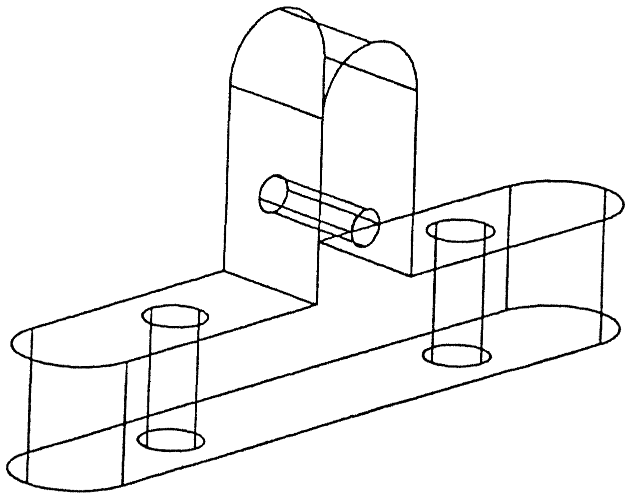


Fig 2.2: Solid model for a simple object

2.2.1.1. Boundary Representation

A boundary representation (b-rep) model is based on the topological notion that a physical object is bounded by a set of faces, which are regions or subsets of closed and orientable surfaces. Topologically, a boundary model of an object is comprised of faces, edges, and vertices of the object linked together in such a way as to ensure the topological consistency of the model.

The database of a boundary model contains both its topology and geometry. Topology is created by performing Euler operations and geometry is created by performing Euclidean calculations. Euler operations are used to create, manipulate, and edit the faces, edges, and vertices of a boundary model. Euler operators, ensure the integrity (closeness, no dangling faces or edges etc.) of boundary models.

Geometry includes coordinates of vertices, rigid motion and transformation (translation, rotation etc.) and metric information such as distances, angles, areas, volumes, and interior tensors.

Euler suggests the following equation for a topologically valid solid model that are homomorphic to a sphere (i.e. their faces are non-self-intersecting and belong to closed orientable surface)

$$F - E + V - L = 2\,(B - G) \tag{2.1}$$

Where F, E, V, L, B, and G are the number of faces, edges, vertices, inner loop, bodies, and genus (handles or through holes) respectively.

B-rep is based on the winged edge structure. A general b-rep model of a given solid model is shown in figure 2.3, which consists vertices, edges, loops, faces, genuses, body along with their number and b-rep structure for that solid model is shown in figure 2.4, which consists the connection among vertices, edges, loops, faces, genuses, and body.

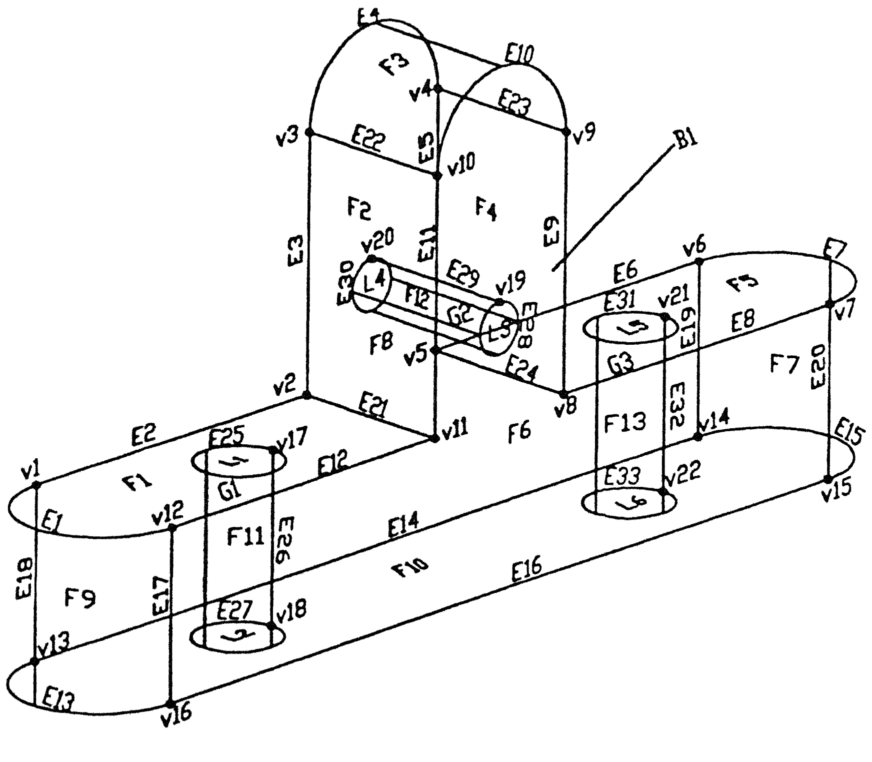


Fig 2.3: A general b-rep model for a simple solid model

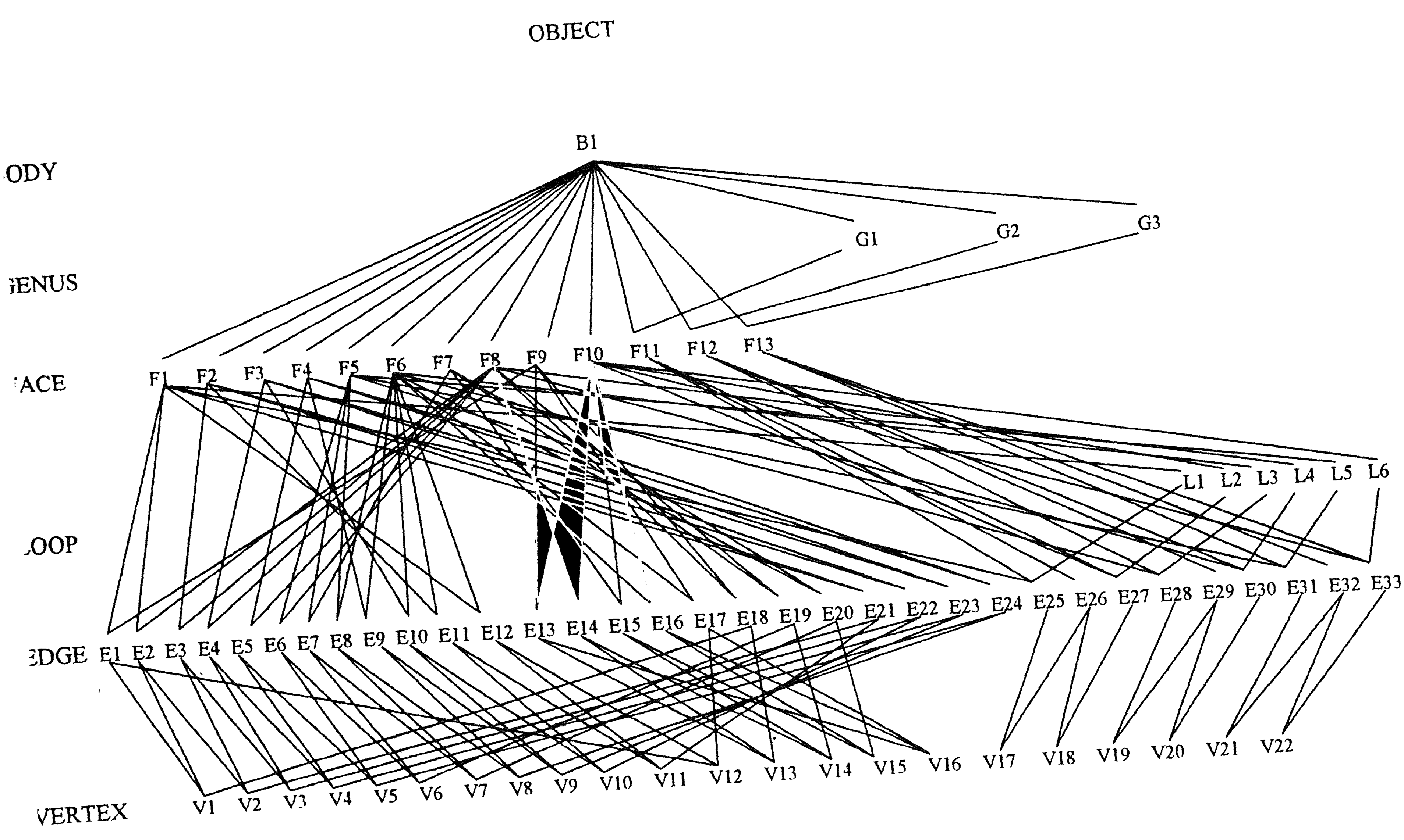


Fig 2.4: A general b-rep structure for a given solid model

Advantage:

i. It is very appropriate to construct solid models of unusual shapes that are difficult to build using primitives.

ii. It is relatively simple to convert a B-rep model into a wireframe model because the model's boundary definition is similar to the wireframe definition.

iii. Algorithms based on B-rep are reliable and competitive than CSG.

Disadvantage:

i. It requires large amount of storage because it stores the explicit definition of the model boundaries.

ii. It is also a more verbose than CSG.

2.2.1.2. Constructive Solid Geometry

A constructive solid geometry (CSG) model is based on the topological notion that a physical object can be divided into a set of primitives (basic elements or shapes) that can be combined in a certain order following a set rules (Boolean operations) to form the object.

The database of a CSG model, similar to B-rep, stores its topology and geometry. Topology is created via the Boolean operations that combine primitives. The geometry includes configuration parameters of its primitives and rigid motion and transformation.

Data structures of most CSG representation are based on the concept of graphs and trees. CSG graph has a succinct data structure to represent a sold model and is suitable for convenient and efficient editing of the model, but it is not suitable to use in geometric computation. A CSG tree is less symbolic and more evaluated data structure to use in computation and application algorithms. A CSG tree is defined as an inverted ordered binary tree, whose leaf nodes are primitives and interior nodes are regularized set Boolean operations. If a solid has n primitives, then there are n-1 Boolean operations for a total of 2n-1 nodes in its CSG tree. A general CSG model for a given solid is shown in figure 2.5, which consists different primitives at their locations.

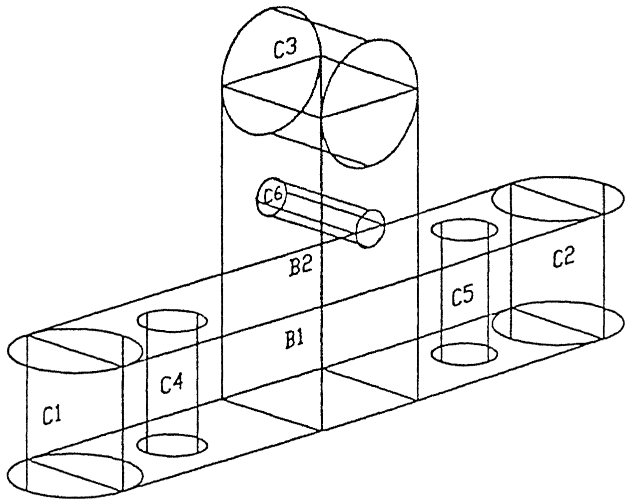


Fig 2.5: A general CSG model for the given solid model

Application algorithms must traverse a CSG tree that is, pass through the tree and visit each of its nodes. The reverse postorder seems the ideal traversal method of a CSG tree. In this method, the leftmost leaf node of the tree has the highest node number in the tree. A general CSG tree for a given solid model is shown in fig 2 5, which consists the Boolean operations between these primitives.

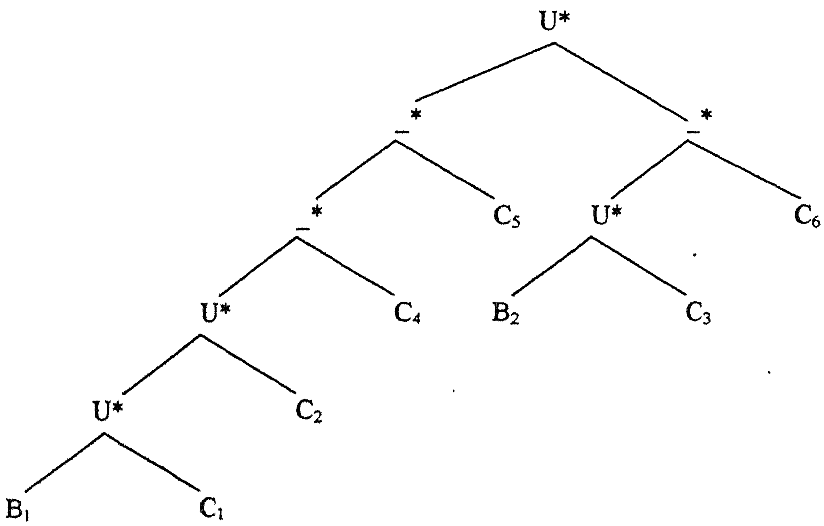


Fig 2.6: A general CSG tree for a given solid model

Advantage :

i. It is easy to construct out of primitives and Boolean operations.

ii. It is concise and requires minimum storage to store solid definition.

Disadvantage :

i. Its inability to represent sculptured surfaces and half-surfaces.

2.2.2 STL file

A standard interface is needed to convey geometric descriptions from various CAD packages to RP systems. The STereoLithography (STL) file, as the de-facto standard, has been used in most RP systems.

The STL file conceived by 3D systems USA, is created from a CAD database via an interface on the CAD system. The STL file format is a boundary representation of 3D-volume geometry using an unordered list of triangular facets. Each triangular facet contains the coordinate of its three vertices and a surface normal pointing away from the material. Triangles are the lowest common denominator in 3D geometric modeling systems, and given the requirements that 3D models from any CAD system should manufactured. Topology can be used to reduce the redundancy present in the STL file format. There are two STL file formats, one is the ASCII format and the other is the binary format. The size of an ASCII STL file is larger than that of the binary format, but is human readable [Kai96]. A STL file for shoe sole is shown in figure 2.7.

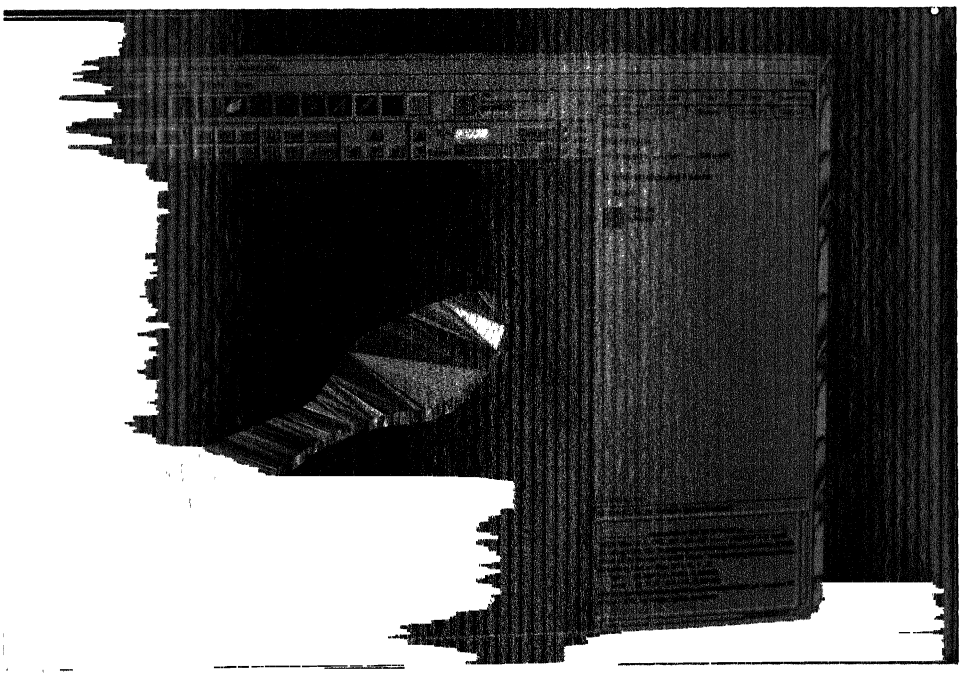


Fig 2.7: STL file for shoe sole

The quality of STL file depends on the deviation of the tessellated surface from the actual surface. To control this, two parameters are specified as follows·

- Chord Height

It specifies the maximum distance between a chord and a surface. The smaller the chord height specified, the less deviation from actual part surfaces. The chord height must be within the following range: the lower bound for the chord height is the function of part accuracy, and the upper bound corresponds to the part size (figure 2.7). The part size is defined as the diagonal of an imaginary box drawn around the part.

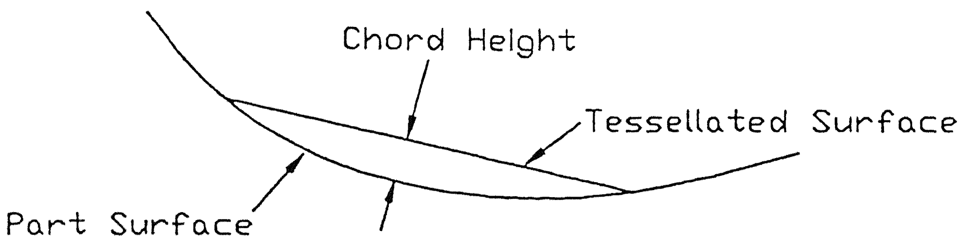


Fig 2.8: Chord Height

- Angle Control

Regulates how much additional improvement provides along curves with small radii. Specifically, it tessellates curves that have a radius (r) defined as:

$$r < r_0 = \frac{partsize}{10}$$

to achieve a maximum chord height of :

$$\left(\frac{r}{r_0}\right)^{\alpha} ChordHeight$$

where α is the Angle Control value. Thus, α=0 results in no additional improvement for curves with small radii. When the system bounds a surface feature by a curve with very small radii relative to its part size, such as a dimple on a golf ball.

2.3 PROCESSING

The processing is the one of the major step in rapid prototyping processes. It contains all the steps from software of the RP machine to physical part creation. In FDM, the processing contain the three steps [FDM96].

- SSL File creation.
- SML File creation.
- FDM hardware.

2.3.1 SSL File Creation

The SSL is the acronym for Stratasys Slice Language. In all layered manufacturing (LM) processes, a CAD model of the part to be built is required. Currently, .STL , a faceted model, is the input CAD data. The .STL model is then mathematically sectioned (sliced) into a series of parallel cross-section pieces by intersecting it with a set of horizontal planes. Algorithm for the slicing, compute intersection curve between a model and a plane, which are described in annexure 1. Each horizontal slicing plane yields a planar contour, which is piecewise linear. Each slice contains closed, nonintersecting, simple contours and normal vectors have a consistent orientation, e.g. that they point towards the outside of the model. Material is deposited in the interior of the planar contour and the part 'grows' incrementally to its final shape. The region between two adjacent slices is referred as a layer. The smaller the layer thickness, the more accurate is the part, but build time is more. The error associated with the staircase effect can be quantified by considering the cusp height.

The cusp height of a layer L with B_{LM} (boundary of LM part) is defined as the maximum distance between B_{LM} and B_{OR} (boundary of original CAD model).

The maximum cusp height of the object is δ and is associated with top-most layer. Various research have been done for adaptive slicing for solving the problems related with peaks, flat areas, stair-case effect etc. The layer thickness plays a major role of the part accuracy and fabrication time. After creating the slices, any existing open curves are corrected using EDIT panel. In the SSL file, closed curves and open curves are shown as red curves and yellow curves respectively. After creation of slices, support and base is created. The green color and blue color curves are support

and base curves respectively. The following steps are provided for the creation of valid SSL file.

- Slice Curves Creation

Slice interval, is a slice width between the two layer. In Quickslice software, default slice interval is 0.01inch. The selection of slice interval depends on the part height and the part accuracy. Minimum slice interval is used for improvement of surface finish but it is also increased the total manufacturing time of the part.

If any open curve is found in any slice, then editing of slice curves is required.

- Editing of Slice Curves

For editing of slice curves, the Quickslice software provides the following utilities.

- Delete Curve.
- Copy Curve along the X & Y-axes and in Z-axis.
- Close Curve.
- Merge Curve
- Trim Curve
- Split Curve.
- Vertex Operations
- Fix Spikes.
- Offset.
- Transform Operations on Slice Curves
- Transform Operation on Entire Part
- Drawing Slice Curve

After editing, save the improvement in SSL file for future use.

- Supports Creation

When a model has a part of its geometry without a solid surface underneath it, supports might to be required. Supports are structures designed to hold a bead of material up while it is extruded. After the model is finished, the supports are removed, leaving the supported section of the model in place.

There are many methods to create supports. The kind of supports needed for a model is determined by the specific geometry of the part. Direct and containment supports can be created for the model. For a specific region, supports can be created manually as well as it can be created as part of the CAD/CAM program and imported as part of the STL file.

The support panel contains several options for creating and editing supports.

- Base Creation :-

It crates release material base underneath the entire part. The base can be any number of layers thick and also offset larger than the part. The base panel contains some options, which affects the base creation .

After creation of slices of parts, supports, and base the file is saved as *.ssl file. A SSL file for shoe sole is shown in figure 2.9.

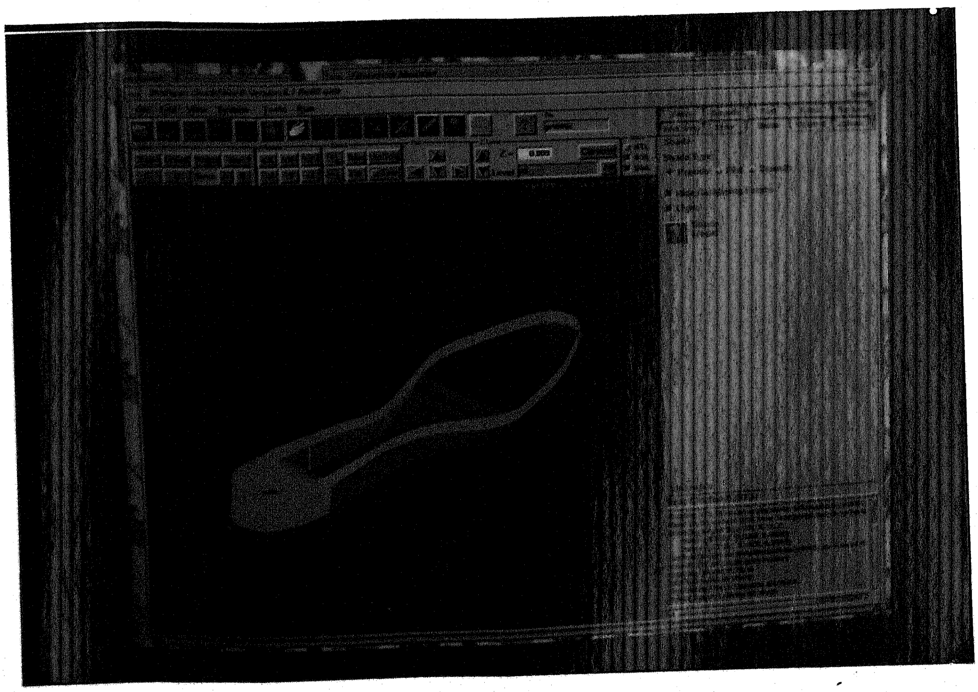


Fig 2.9: SSL file for shoe sole

2.3.2 SML File Creation

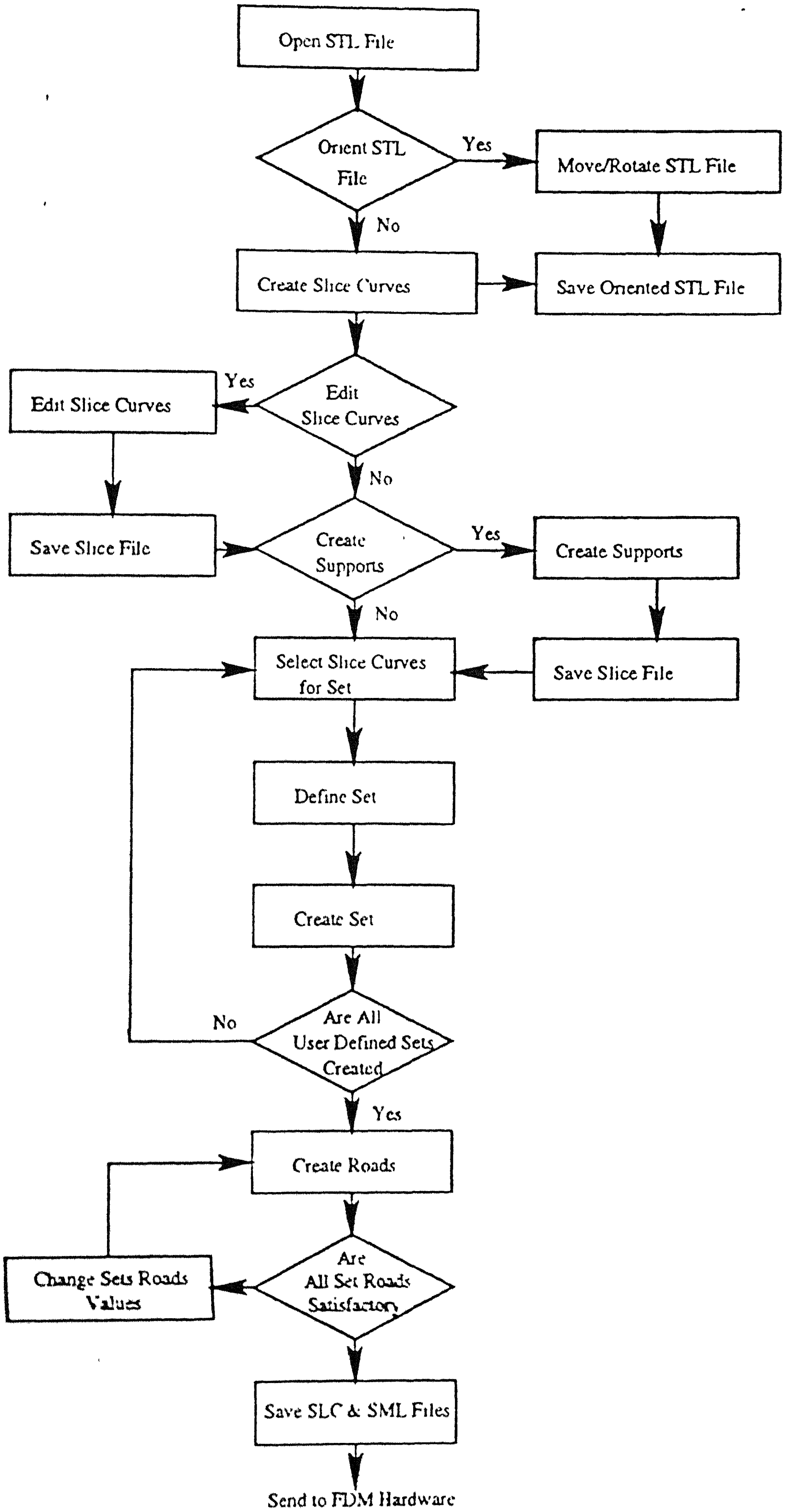


Fig 2.10: Overall procedure for the creation of SML file

The SML is the acronym for Stratasys Machine Language. This file contains the actual instruction code for FDM hardware. SML file orders the FDM to take a specific tool path at each Z level. These tool paths are called Roads. Before a part sent to the FDM hardware, roads should be created properly. There are different parameters of hardware, which affects the accuracy, build time etc. of part.

After setting the all the parameters, the Quickslice software creates the roads, as SML information. At the time of saving the SML file, software itself tells about how much time it takes, and how much model material as well as support material it takes. The overall procedure for the creation of SML file is shown in figure 2.10.

2.3.3 FDM Hardware

The FDM-1650 is a bench-top unit and can be placed next to a CAD workstation, shown in figure 2.11, as it requires no exhaust dust or other special accessories. The FDM head has two nozzle, one for main material and other for support material. The liquefire in the head melts the material at the temperature of 270° C for model material and 265°C for support material. The model is built in a closed cabinet maintained at 70°C.

The head is mounted on a carriage which moves in x and y direction. The z movement is given to Z-stage platen. The model rests on the foam foundation provided on Z-stage platen. Both the model and support materials come in a wire form, from two different material spools located at the rear of the machine. On the front panel all the control buttons are provided to set the machine as per requirement. The controls such as x, y, z movement, temperature control, loading and unloading of material, etc. are available.

To run the FDM machine, first the nozzles tip and the machine is cleaned. After sending the SML (Stratasys Machine Language) file, the initial x, y, z position of modeler tip is set properly with respect to foundation foam and the FDM machine is allowed to run. The head movement and material flow information for each slice curve is downloaded to the FDM-1650. The FDM head deposits a perimeter road, which follows the shape of a slice curve. After the perimeter road, the head follows fill roads, which fill the solid areas inside the part. When a layer is deposited completely, the ... of slice thickness and the process is repeated.

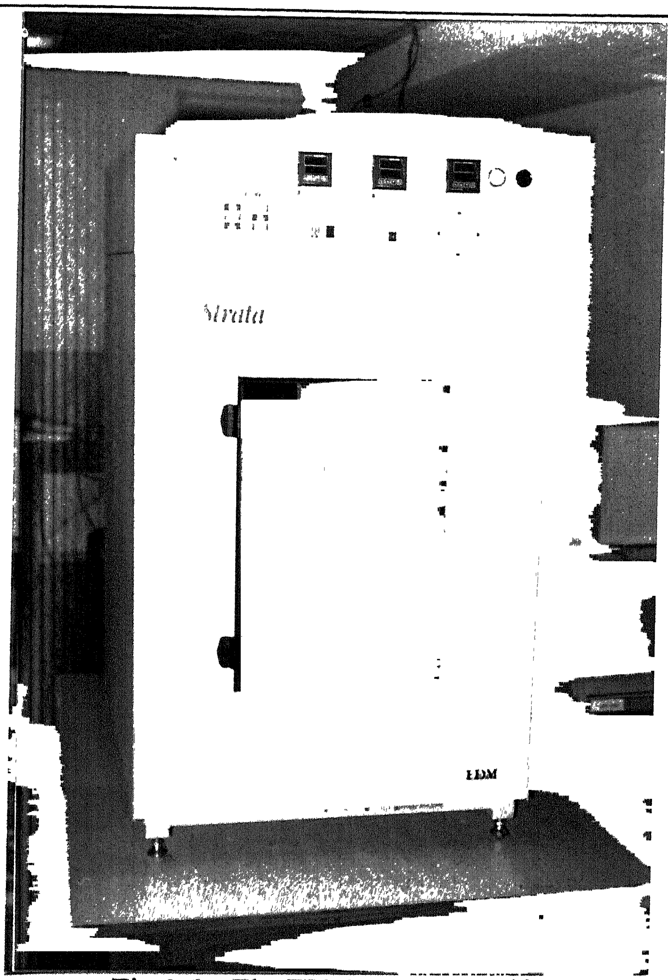


Fig 2-8: The FDM – 1650 Machine

The FDM-1650 features the Break Away Support System (BASS), allowing the designer to create models with greater speed and precision. BASS uses a second nozzle to extrude the support material. The supports are designed to prop-up the overhanging portions of the part during modeling. The head automatically extrudes the support tip out wherever required. The supports are detached easily, making the finished product look better with minimum post-modeling finishing.

Model Material

The FDM-1650 is capable of using inert, nontoxic material such as Investment Casting Wax and P400 Plastic (ABS Plastic). In the present work, P400 plastic is used for model making, as it is a tough plastic, which produces sturdy prototypes. P400 plastic is an Acrylonitrile Butadiene Styrene (ABS) based material having the properties given in Table 2.1.

Tensile Strength	34.5 MPa
Flexural Strength	65.5 MPa
Tensile Modulus	2482.8 MPa
Flexural Modulus	2620.7 MPa
Melting Point	270°C
Softening Point	104.4°C
Specific Gravity	1.05 gm/cc

Table 2-1: Properties of P400 – ABS Plastic

The material is wound on a spool in the form of a filament approximately 1.8 mm in diameter, so it is both easy to load and easy to store. The material changeover for Stratasys system is relatively quick and simple, with little material wastage.

2.4 POST PROCESSING

The post processing of the part consists of the finishing or more appropriately is finalising the part. It contain removal of the support material from the model, surface finishing of the model etc. These models can be polished and finished either by mechanically or chemically.

In mechanical finishing, the surface of the model are smoothened and the seams are removed with an abrasive such as sand paper, scoth-brite, flat file, or tools such as a hard-held razor knife. A razor knife work well, especially in removing seams. An electric waxer, a hot melt knife, is an excellent tool for removing thin hair-like strands "spider webs". It can also be used to patch up blemishes or remove supports.

In chemical finishing , solvents such as paint thinner, acetone , heptane, and toluol smooth the surface of the model by chemically dissolving the rough edges, and also bond the layers together. Epoxy is a two-part chemical, a mixture of polyester resin and styrene monomer, which coats the model and creates a hard shell, giving it a smoother appearance and provides reinforcement for the model. But epoxy has a high thermal reaction temperature, which may deform a model with thin walls. Spray paint will accomplish the same smoothing effect as epoxy, but doesn't add reinforcement. By applying on epoxy pre-coated model, spray paint gives the model an extremely smooth

Chapter 3

MOLD DESIGN AND ANALYSIS

3.1 INTRODUCTION

Mold design is a crucial step in creation of molds of a part. It involves various parameters, which affect the manufacturability of molds. Mold design can be verified by the FE analysis. The verification of the stresses, deflection and other critical factors, which affects the life, accuracy of products, reproductionability etc, can ensure a good mold design. Aim of this analysis is to do comparative study between conventional molds and RT molds for injection molding. Conventional molds are normally made of Gunmetal; whereas epoxy resins with some filler material and TAFA coat are used for RT molds. The analysis predicts the effect of various parameters (TAFA coat and the inclusions) on the strength of epoxy molds. Evidently one can use either an experimental technique or a numerical technique. Experimental techniques are not only difficult, but also will not be cost effective. Also the experimental setups may not be available ready-made. In contrast a numerical technique like "Finite Element Technique" will be of great use for the analysis.

3.2 FINITE ELEMENT METHOD

Finite Element Method is a powerful numerical technique to get approximate solution for problems of continuum mechanics. Inherently, it is approximate, since a continuum with infinite number of degrees of freedom is replaced with a discrete system with finite number of degrees of freedom. The continuum is broken into a finite number of regions called elements, connected at finite number of points called nodes. An approximate admissible solution is constructed over the assemblage of elements, and the solution continuity is maintained at the inter-element boundary.

The following steps are essential in a typical FEM formulation

3.2.1 Discretization and Approximation

This is the mesh generation step. Here depending on the nature of the problem element type is selected and their number controls the convergence. Too coarse mesh will give inaccurate results, whereas a very fine one will take lot of CPU time to solve. The type of approximating function is also selected in accordance to the nature of the problem. Using these informations so called shape functions or interpolating functions are found out.

3.2.2 DOF per Node and Boundary Conditions

Every element has associated Degrees of Freedom to its nodes. It could be translational and/or rotational. The boundary conditions are decided by the physical modeling of the real life problem.

3.2.3 Formulation of Elemental Matrices and their Assembly

By knowing the material properties, DOF and the load, elemental coefficient matrix, DOF matrix and elemental right side vectors are formed. This is evaluated for each and every element. After formulation, the elemental matrices are assembled and global matrices are formed. The final form will be as shown below.

$$[K]\{\Delta\}=\{F\} \tag{3.1}$$

where, [K] is global stiffness matrix

$\{\Delta\}$ is the displacement vector

$\{F\}$ is the global right side vector

3.2.4 Applying Boundary Conditions

After assembly, the boundary conditions are forced on the global matrices and a sparse matrix is prepared.

3.2.5 Model Solution

The sparse matrix is then solved using any robust numeric scheme [Reddy93].

3.3 PROBLEM FORMULATION

Not less than 75% of the components of footwear industry are processed by Injection Molding. This is the most common process and hence, for the purpose of analysis, this process is chosen. To recap, the main idea behind this work is to reduce the stress concentration as well as compare among gunmetal mold and epoxy molds. Various parameters are being the TAFA coat and /or the filler materials, which affect the strength of an epoxy mold. Based on these parameters, there are following cases:

- Gunmetal
- Epoxy alone
- Epoxy with TAFA coat
- Epoxy with different filler materials in various proportion

In practice, aluminum and steel are the common materials used as inclusions for altering the properties. Other fillers like wood or plastic would be for reducing the cost and will serve nothing to strength. So, only aluminum and steel particles are being considered. Equally important is the amount of the filler material. Volume Fraction will be a measure for the same. Typically the filler materials are used with 30 %, 50 % or 90 % of volume fraction in some cases for special purpose. Therefore, the molds generated with and without TAFA coat, are as follows.

- Epoxy with 30 % Aluminum granules
- Epoxy with 50 % Aluminum granules
- Epoxy with 90 % Aluminum granules
- Epoxy with 30 % Steel granules
- Epoxy with 50 % Steel granules
- Epoxy with 90 % Steel granules

3.3.1 Restraints

The mold is having temperature as well as static restraints. The cavity is having injection temperature and all other outer faces are having room temperature as temperature restraints. The mold is rigidly fixed in the base. So, base is restricted by all the six degree of freedom and the upper face of the lower die is restricted by all degree of rotation, as static restraints.

3.3.2 Force modeling

During injection uniform hydrostatic pressure will prevail in the mold cavity. So, uniform pressure is applied on the mold cavity. As there clamping pressure is applied on the upper face of the upper die. So, its effect is determined by some interpolation.

3.3.3 Material Properties

Mechanical properties of standard materials Gunmetal, Aluminum granules, Steel granules, MCP-400 are given in the table 3.1.

S. No.	Properties ⇨ Material ⇩	Tensile Strength (MPa)	Poisson's Ratio	Tensile Modulus (MPa)	Density (Kg/m^3)
1	Gunmetal	200	0.32	105,000	8,800
2	Epoxy	55	0.35	3,500	1,200
3	Aluminum Granules	80	0.34	71,000	2,710
4	Steel Granules	460	0.29	210,000	7,860
5	MCP-400	110	0.27	65,000	---

Table 3.1: Mechanical properties of standard materials

The epoxy with particulate fillers is a classical example of a particulate composite. Here the dispersed medium is epoxy and dispersed particles are aluminum (or steel). Such a composite will behave as an isotropic material. No direct empirical relations are available for estimating the mechanical properties of particulate composites that too particularly for Metal-in-Plastic type composites. But, experimental results are available for "Aluminum based particulate metal-matrix composites" [Deol93].

As per the rule-of-mixture bounds, the modulus of a two-phase composite composed of phases A and B should fall between an upper bound, given by

$$Ec = VmEm + VpEp \tag{3.2}$$

and a lower bound, given by

$$Ec = \frac{EmEp}{VmEp + VpEm} \tag{3.3}$$

Where E_c = Tensile modulus of composite

E_m = Tensile modulus of matrix

E_p = Tensile modulus of particle

V_m = Volume fraction of matrix

V_p = Volume fraction of particle

In fact, all other properties will also follow the same pattern. The first situation is realized in fiber-reinforced composite materials, whereas, the latter one is typified by particles in a matrix. So, the later one equation is used for calculating the properties of epoxy resin with filler materials, where epoxy resins used as matrix and filler materials used as particles. The calculated properties are described in the table 3.2.

S. No.	Properties ⇨ Material ⇩	Tensile Strength (MPa)	Poisson's Ratio	Tensile Modulus (MPa)	Density (Kg/m^3)
1	Epoxy + 30% Al	56.34	0.347	4,900	1,360
2	Epoxy + 50% Al	61.54	0.345	6,670	1,585
3	Epoxy + 90% Al	75.47	0.341	24,244	2,373
4	Epoxy + 30% Steel	68.25	0.33	4,965	1,508
5	Epoxy + 50% Steel	90.2	0.317	6,880	1,961
6	Epoxy + 90% Steel	252.75	0.295	30,440	4,970

Table 3.2: Mechanical properties of Epoxy resins with filler

3.4 I-DEAS SIMULATION TOOL

I-DEAS Master Series™ is trademark of "Structural Dynamic Research Corporation (SDRC) USA". It is a well-known package for solid modeling and simulation. It comprises of many modules for modeling, manufacturing applications, finite element simulation, rapid prototyping and so on. I-DEAS Master Series™ simulation tools provide access to powerful geometry construction and editing capabilities, extensive capabilities for building models, and a wide selection of solutions to simulate real world conditions. The whole package is built with concurrent engineering concept. At any time if the original design changes automatic updating of finite element model is done. It means that if at a later stage, the design changes, the mesh will get updated and the boundary conditions will change. Moreover the software handles boundary conditions by geometry rather than by nodes and elements. This makes the process of applying loads and restraints very simple. Important tools for simulation include [I-DEAS]:

- Geometry tools
- Modeling tools
- Integrated solvers
- Post processing tools

3.4.1 Geometry Tools

The I-DEAS Master Series software uses the master model directly for simulation. The non-manifold topology foundation of the software allows usage of wireframe, surface and solid geometry at any time, as appropriate for model building.

3.4.2 Modeling Tools

Having prepared the geometry appropriate for analysis, a finite element model has to be generated. Below is a brief discussion on these tools. More details can be found elsewhere.

Meshing the most important and time-consuming step. Simulation provides automatic, mapped and manual meshing methods. They can be combined as needed to produce appropriate models. I-DEAS has a rich element library. There are beam elements, shell elements and 3D solid elements. The selection of element type and

number of elements is very critical for any finite element solution, as a compromise has to be made between accuracy and computing time. I-DEAS has very powerful tools to get an accurate result with less computing time.

Thin-shell elements and beam elements are abstractions of the 3D physical model. Thin-shell elements are abstracted to 2D elements by storing the third dimension as a thickness on a physical property table. Beam elements are abstracted to 1D elements by storing the 2D cross-section as separate beam section property. Each level of abstraction takes more preparation time, but reduces the solution time. 3D solid elements predict 3D stresses accurately. Modeling them is also simple. But they need intensive computations. Understanding the behavior of each element type helps to make the best modeling decisions. In the present work, 3D solid elements are used for die meshing and 2D thin shell element are used for creating the effect of metal spray. I-DEAS supports tetrahedron element with different orders for 3D solid elements and triangular as well as quadrilateral element with different order for 2D-shell element.

In the present work, parabolic tetrahedron element with 10 nodes is used for 3D solid mesh and parabolic triangular element with 6 nodes is used for shell meshing.

3.4.3 Integrated solvers

I-DEAS has different in built solvers for different kind of problems. Some of them are I-DEAS Master Solution - Linear™, I-DEAS Master Solution-Nonlinear™, I-DEAS TMG™, and I-DEAS System Dynamics Analysis™. The solution algorithm includes both sparse matrix and iterative solver. Apart from this it interfaces with external solvers like ABAQUS™, ANSYS™, Cosmic NASTRAN™ also.

3.4.4 Post Processing Tools

Understanding the results is the most important and critical task in a Finite Element analysis. With out good interpretation, even an accurate solution will be futile. The Post Processing Task and the I-DEAS Visualizer™ provide a wide range of graphical techniques for displaying the results data. All kind of picture files and even movie files could be prepared with the results. So animations can be stored for future applications as a standard movie file.

3.5 FE ANALYSIS

3.5.1 Geometric Modeling

To analyze the effect of the filler materials a fairly simple component shown in figure 3.1, is taken as a pattern. It is picture of shoe sole with the basic wireframe being a spline.

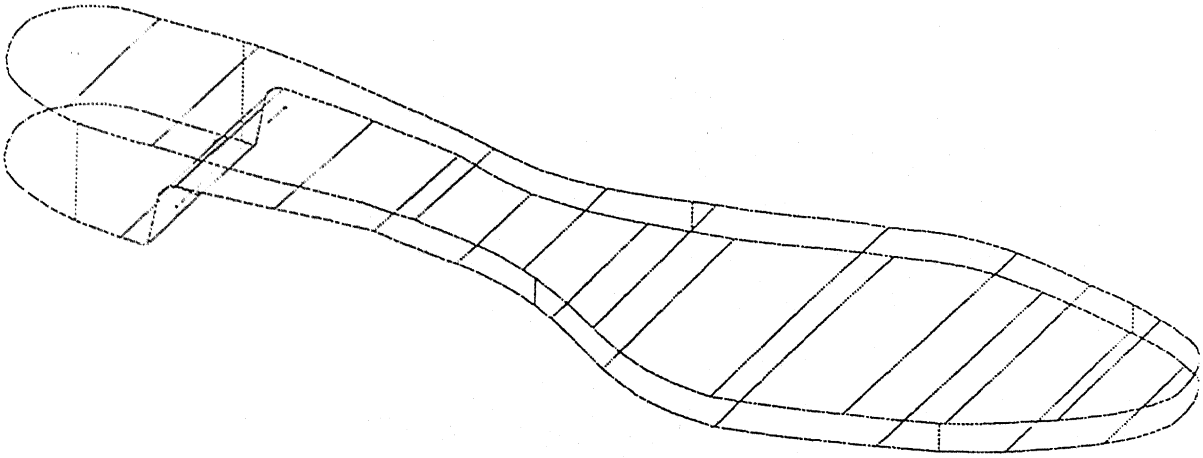


Fig 3.1: Pattern of Shoe Sole

With this, a mold is created using Boolean Operation in the simulation module of I-DEAS Master Modeller™. Dimensions of the mold are 81 x 126 x 296 mm. The mold is shown in figure 3.2.

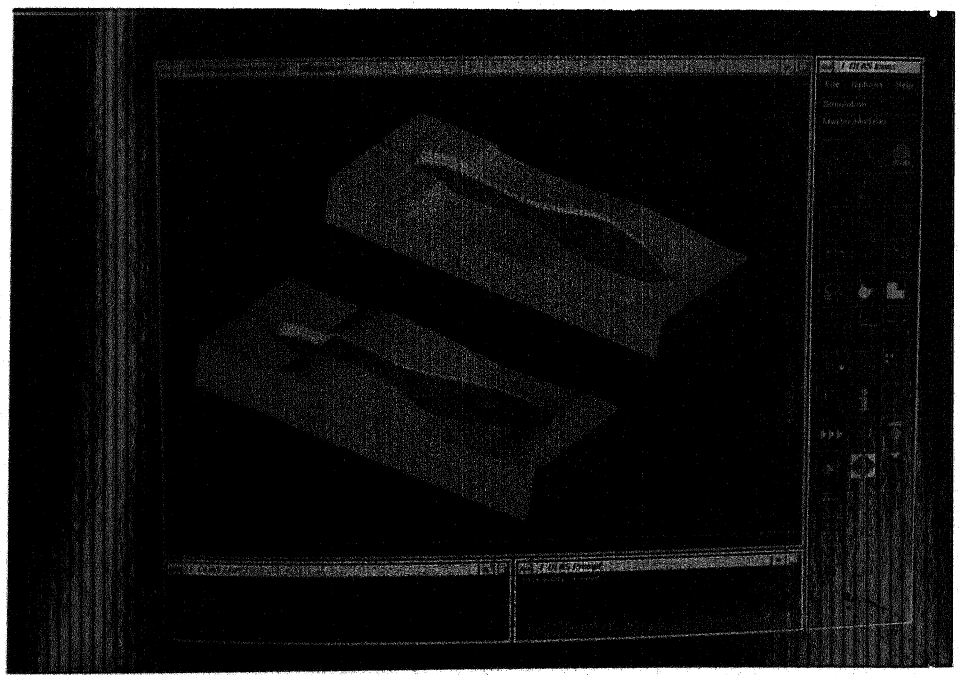


Fig 3.2: Mold for the Shoe Sole

3.5.2 Boundary Conditions

As explained in the section entitled " Problem Formulation", the loads and restraints are applied on according faces. The mold is splitted in two pieces. Due to the geometric symmetry existence in the mold, the lower part of mold is used for the analysis for reducing the computation intensity. Analysis gives the most critical regions regarding maximum principal stresses and deflection, which helps in more accurate results. Bottom face of the part is restricted by all the six degrees of freedom and the upper face of part is restricted by all the degree of rotation (figure 3.3). Whereas, cavity is restricted by uniform injection pressure (i.e. 300 bar) (figure 3.3). And clamping force (i.e. 932.4 KN) is also simulate on the upper face except the cavity. Following picture depicts the restraints and force boundary conditions.

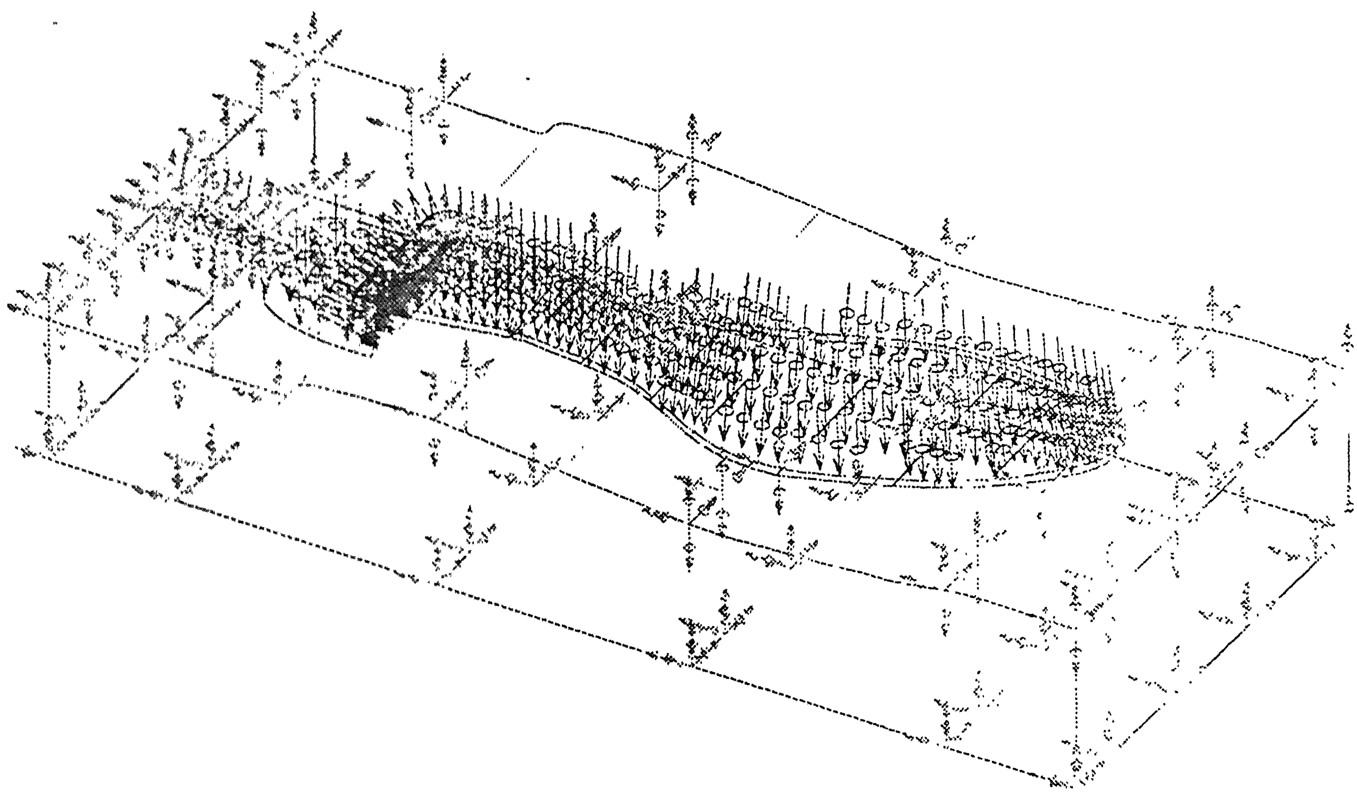


Fig 3.3: Restraints and Pressure on the lower part of mold

3.5.3 Mesh Generation

A solid mesh, of parabolic tetrahedron element having 10 nodes with 15-mm element length, is generated on the whole volume. This mesh contains 10910 nodes and 6991 elements. And a thin shell mesh, of parabolic triangular element having 6 nodes with 15-mm element length and 3 mm shell thickness, is generated on the upper face for the metal spray condition. This mesh contains 556 elements except than solid mesh. These numbers of nodes and elements are reached after many trials using I-DEAS Simulation tool. In this analysis, convergence become more critical as basic wire-frame entity, used to create this solid model, is a spline, which is difficult to approximate geometrically. The mesh is shown in figure 3.4.

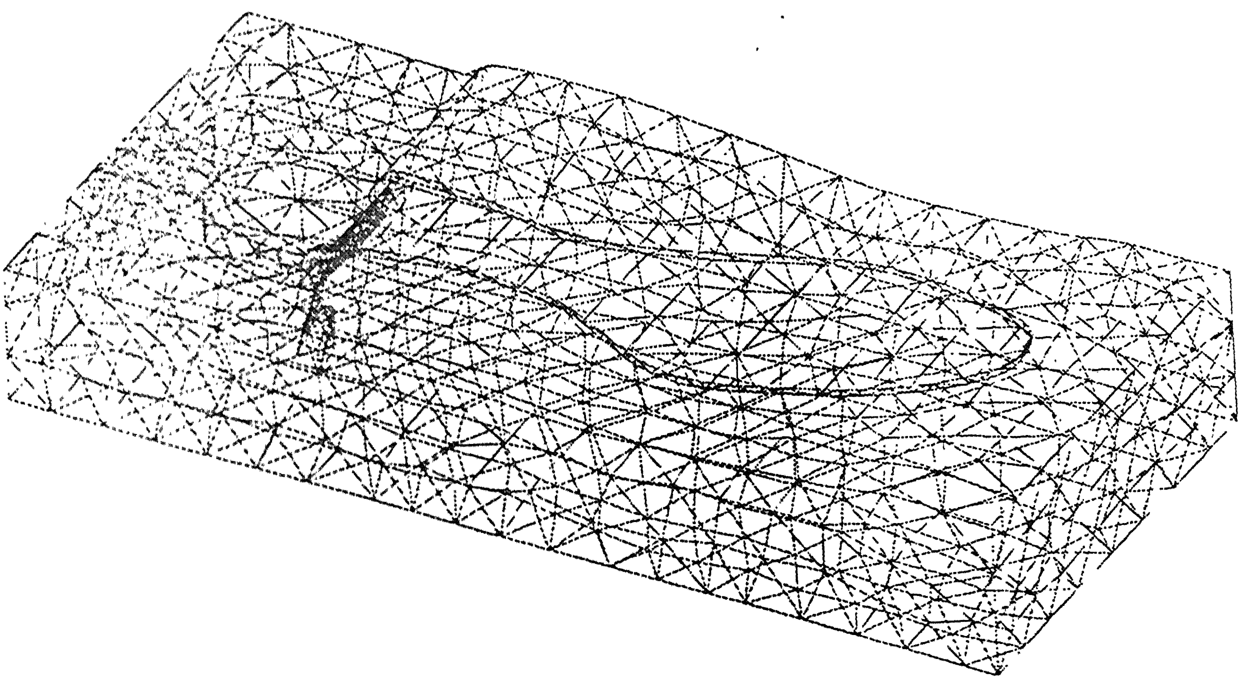


Fig 3.4: FE mesh for the mold

3.5.4 Theory of Failure

There is no well-defined theory of failure available for particulate composites. But the basic matrix, which is epoxy in this case, is brittle. So, the theory of failure applicable for brittle material can be used. In this context "Maximum Principal Stress Theory" would be the right choice.

Hence in the present work the "Maximum or First Principal Stress Theory" is used as theory of failure.

3.5.5 Post Processing

In injection molding, clamping force is played an important role. Numerically, clamping force is having linear relationship to the total reaction force on contact surface at some translation, in same direction. So, total reaction forces are calculated on the contact surface at 0.01-mm translation, in same direction. Then find out the magnitude of translation of contact surface, by linear relationship between clamping force and total reaction force, which give the same effect as clamping force. Table 3.3 shows the magnitude of total reaction force on contact surface due to 0.01-mm translation in same direction, and magnitude of interpolated translation value.

S. No.	Results ⇨ Material ⇩	Reaction Force (KN)	Translation in negative x-direction (mm)
1	Gunmetal	859.3	0.01085
Without Metallic Spray			
2	Epoxy	29.55	0.3155
3	Epoxy + 30% Al	46.24	0.2016
4	Epoxy + 50% Al	56	0.1665
5	Epoxy + 90% Al	219.7	0.04244
6	Epoxy + 30% Steel	41.03	0.3155
7	Epoxy + 50% Steel	56.15	0.166
8	Epoxy + 90% Steel	243.6	0.03827
With Metallic Spray			
9	Epoxy	31.96	0.2917
10	Epoxy + 30% Al	44.19	0.211
11	Epoxy + 50% Al	59.54	0.1566
12	Epoxy + 90% Al	208.9	0.04463
13	Epoxy + 30% Steel	43.68	0.2135
14	Epoxy + 50% Steel	59.12	0.1577
15	Epoxy + 90% Steel	249	0.03745

Table 3.3: Calculated total reaction force and interpolated deflection

Now, the calculated translation value, on the contact surface with restraints and uniform injection pressures on the cavity are applied. The basis of the stress analysis is depend on Maximum Principal Stress theory. So, the maximum principal stress and deflection is evaluated, which are tabulated in next section.

3.6 RESULTS

The following table gives maximum magnitude of maximum principal stress, maximum magnitude of deflection for the injection molding conditions of molds of different materials. The figures of some results are attached in the annexure 2.

S. No.	Results ⇨ Material ⇩	Max. Principal Stress (MPa)	Deflection (mm) x10^{-2}
1	Gunmetal	65.8	1.36
Without Metallic Spray			
2	Epoxy	63.5	41.3
3	Epoxy + 30% Al	63.5	26.4
4	Epoxy + 50% Al	63.6	17.7
5	Epoxy + 90% Al	64.2	5.94
6	Epoxy + 30% Steel	65.0	28.9
7	Epoxy + 50% Steel	65.9	19.8
8	Epoxy + 90% Steel	67.6	4.65
With Metallic Spray			
9	Epoxy	260	31.0
10	Epoxy + 30% Al	184	22.7
11	Epoxy + 50% Al	104	13.3
12	Epoxy + 90% Al	70.9	4.56
13	Epoxy + 30% Steel	180	22.7
14	Epoxy + 50% Steel	98.03	12.8
15	Epoxy + 90% Steel	66.5	3.97

3.7 FEEDBACK FOR DESIGN

The result show that the main stresses occur at sharp edges, sharp corners. So, these edges, curves, or corners should be changed into the smooth contour. This will significantly improve the design and reduce deflection and stresses. This will improve the life of mold and also provide pleasant looks. The small protrusion and thin wall feature creates stress zone. So, minimization of thin wall and small protrusion features are required.

Chapter 4

RAPID TOOLING METHODOLOGY

4.1 INTRODUCTION

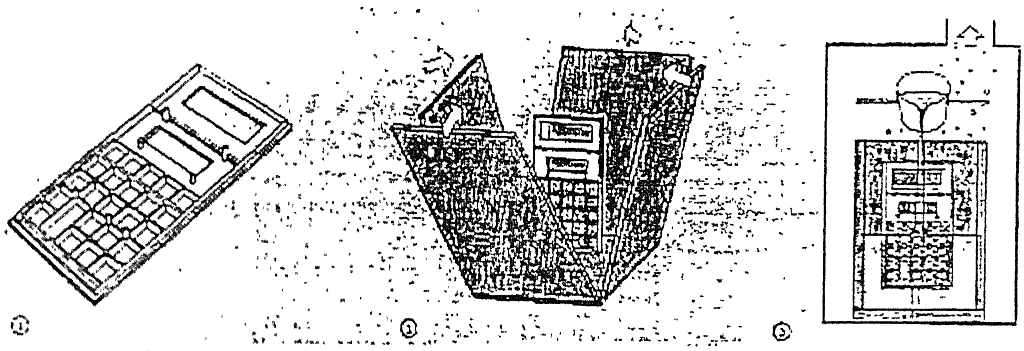
Rapid tooling (RT) is a technology that adopts Rapid Prototyping (RP) techniques and applies them to tool and die making. RT is becoming an increasing attractive alternative to conventional tool making. The move from conventional machining methods for making the tools to rapid tooling is more a leap than a step; similar to moving to computer aided design (CAD) from drafting. RT is useful when tool geometry makes traditional machining difficult because of part complexity or specific geometry features, such as undercuts. Use of a particular RT method depends on the application, for which tool is intended to. For instance, *Epoxy Tooling* can produce injection-molding tools, whereas press tool dies can be produce with low melting alloys. Some RT processes are defined below.

4.2 MCP VACUUM CASTING

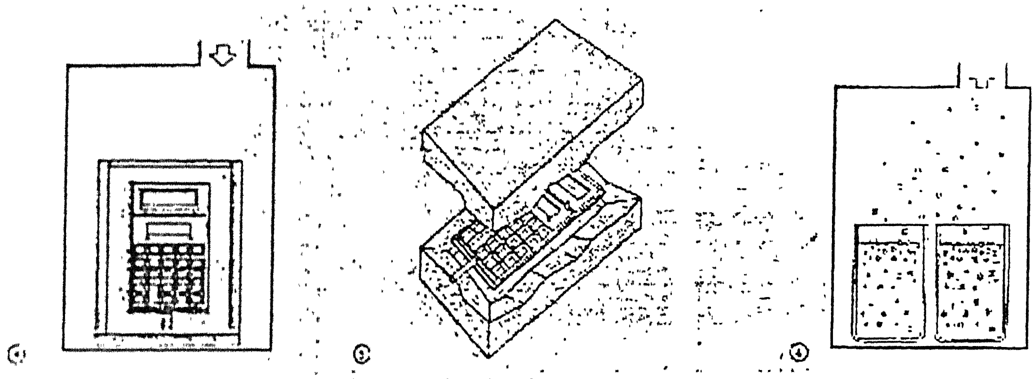
Room temperature vulcanization (RTV) silicone rubber enables fabrication of flexible molds which can be used for manufacturing parts with intricate detail and undercuts. The molds are poured in one step, compared to typical two-part molds that form each half separately. The pattern fitted with gates is suspended in the casting frame. After the RTV-silicone rubber is poured around the pattern, the vacuum chamber de-aerates the rubber to increase dimensional accuracy before it enters the heating chamber for final cure. After cure the mold is cut into two halves. The urethane resin components are placed into vacuum chamber with casting funnels and the mold. The vacuum de-aerates the urethane resins, after which computer controls mix and pour the resin; the heating chamber final cures the mold. The process is shown in figure 4.1. Cycle times average one part one hour. Then mold segments are mounted on an injection-molding machine to produce a few hundred plastic parts.

Silicone rubber molds have excellent chemical resistance, low shrinkage and high dimensional stability, making them suitable for producing parts in polyester, epoxy

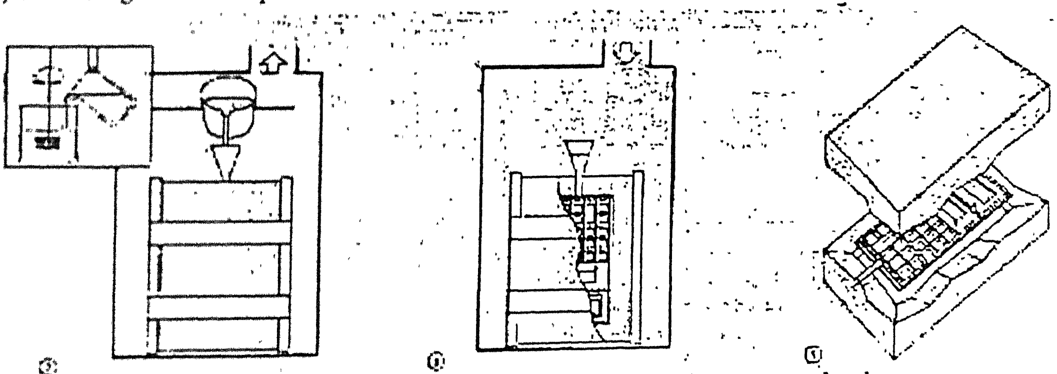
and polyurethane foam by injection molding. They are however, more expensive than cast epoxy or laminated tooling, and therefore economical for small intricate parts or parts with undercuts, which cannot be produced by rigid tooling. Such toolings are best when produced with wall thickness less than 12 mm [Anil98].



1) Patterns are made of any material, metal wood or plaster.
2) Pattern is fitted with the casting gate and setup on the parting line and then suspended in the mold casting frame.
3) Silicone rubber is poured into the mould casting frame around the pattern.



4) The Mould is left to harden inside the heating chamber.
5) The pattern is removed from silicone casting by cutting along the parting line.
6) The casting funnels are placed and the mould is closed and sealed.



7) The computer controlled equipment mixes and pours the resin inside the vaccuum chamber.
8) After casting the resin the mould is moved to the heating chamber.
9) After hardening, the casting is removed from the silicone mould. Gate and risers are cut off to make an exact copy of the pattern. The component can be painted or plated.

Fig 4.1: The vacuum casting process

4.3 MCP LOW-MELTING ALLOY

The MCP low-melting alloy of HEK, GmbH, Germany has been used for the press tool die. These dies are successfully used for making different types of sheet metal parts and also used for processing different types of FRP composites and unidirectional Glass fiber composites. MCP-137 is an alloy that reproduces the surface accuracy or inaccuracies exactly. It has very good releasing properties. For RP pattern, there are only two ways of making the press tool. To produce press-tool die, the RP pattern included with guide pin is kept on the tooling board and side frame is kept around the pattern then forming sand is filled in to the box and rammed properly. Box is then put in the inverted position and side frame is removed. Another side frame with larger height is kept all around it and on the top of it cover plate fixed with all fixtures, needed to attach the tool on the press, is attached. Then MCP-137 alloy is poured into the box completely. After solidification of the alloy, the box is again kept into the original position and forming sand is removed from the box and the upper surface of the first half of the tool (i.e. punch) is cleaned and filed to get the good surface finish.

Now, at this stage an alternative is possible that a steel drawing ring can be integrated into the base tool to increase the tool life. Then second half of the tool (i.e. die) is cast [Rahul99].

For better surface finish, in place of forming sand, plaster of paris can be used. For the larger part, blank holder is used to restrict the distortion.

For sheet metal component, a wax sheet is used. After solidification of the first half, the pattern is removed and then wax sheet around the surface of first half is glued up to the thickness of the sheet metal or composites, which have to be processed on the tool. Then low melting alloy is poured in the box and after solidification of alloy wax sheet is removed and tool is cleaned. The process is shown in figure 4.2.

The press-tool die has been successfully used for making the different types of FRP composites parts made from glass fiber cloth, short fiber and prepreg. Cores made from MCP-137 low melting alloy can be used in MCP-TAFA system in injection molding process. This alloy can be directly poured into the mold made from Silicone rubber and that part can be used for various purposes.

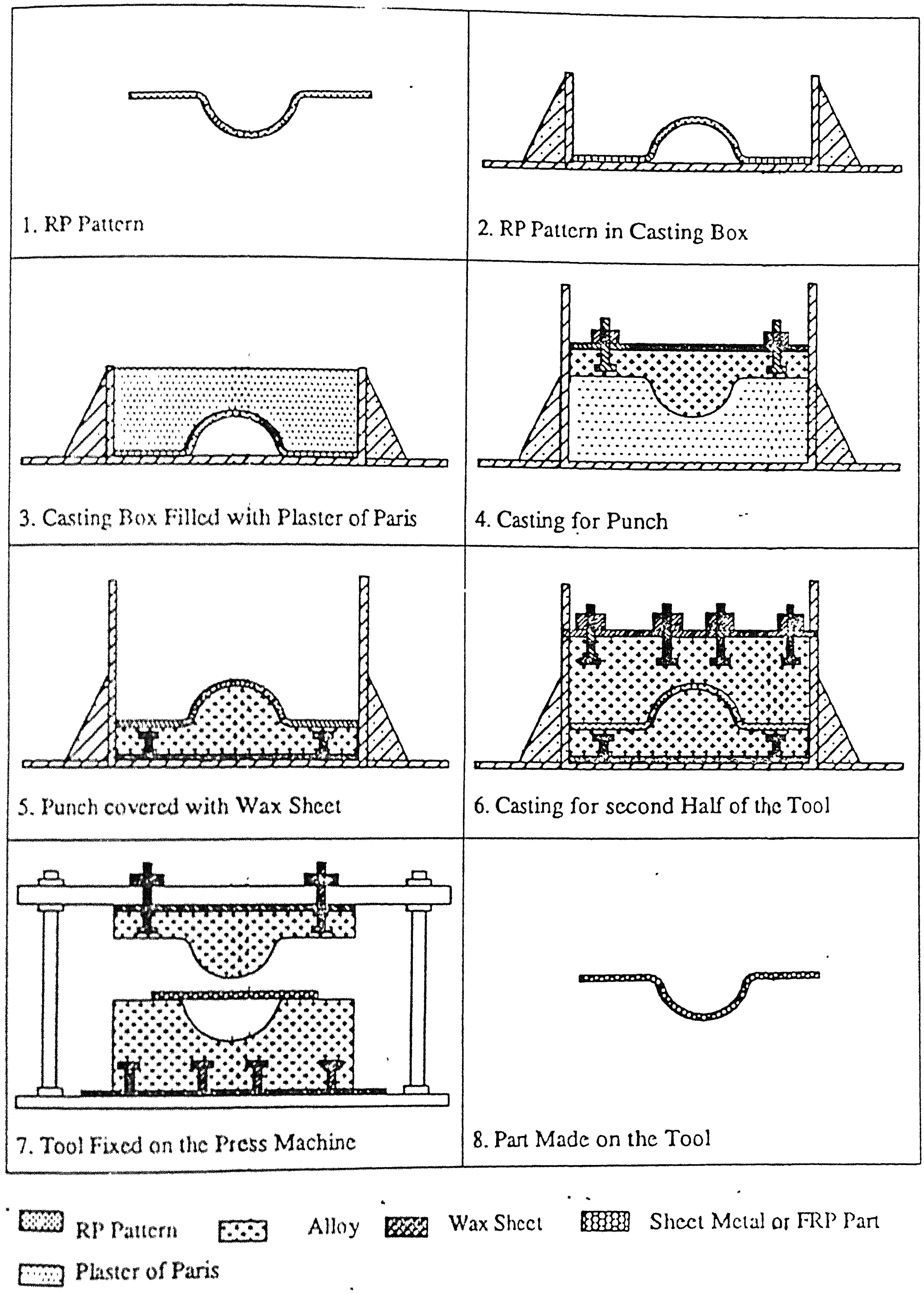


Fig 4.2: Process of making Press-tool using waxsheet

4.4 `EPOXY TOOLING

The term 'Epoxy Tooling' has become very generic in the arena of Rapid Tooling now. The basic process involves, preparation of mold box and then strategically placing the master pattern, which could be made of wood, metal or an RP part. A release agent is applied, to facilitate easy release of the master model. It is imperative that the design aspects such as mold dimensions, selecting of parting surface, orientation, cores and inserts are paid due attention prior to this. An appropriate two component (resin and hardener) epoxy system is cast into the mold box. Fillers such as aluminum and steel are added to the resin to impart hardness, impact strength and wear resistance. Often fillers are used to reduce the amount of resin also. After the hardening, curing, and post curing, master model can be easily removed giving us the necessary profile [Dhande98].

Many variations are seen depending on the resin used, fillers incorporated, curing fashion, whether or not any surface coating is done, so on and so forth. But the most common item in most of the process is the basic polymer matrix used. Epoxy, as it is widely called are chemically epoxide resins also called, as ethoxyline resins occasionally, are one of the successful engineering plastic in the polymer clan. The main attracting features of them is their high compressive strength, and superior chemical resistance. Apart from the general epoxies special varieties like thermally conductive, electrically conductive are also available. The main producers of epoxy are Bakelite, Ciba-Geigy (Araladite), Dow and Shell (Epikote), Polycast Industries, Inc.

Some conventions: -

The term 'tooling' in this context refers to making molds for injection molding, blow molding, vacuum forming and for similar applications. Actually, there are many practices in the industry to prepare such tools.

The term 'master model' refers to the basic component desired out of the tool. This could be made up of wood, metal or it could be a 3D solid model also.

The term 'master pattern' refers to the modified master model. Modifications involve providing draft angle, shrinkage allowance and other things, to make the model feasible to the process to be used. This could be made up of wood, metal or it could be a RP component also. Out of this the RP way is found to be the best way in general.

Over the world, epoxy tooling spells differently in different places. There are a number of Epoxy Tooling processes [Sridharan98]. In which, the Metal Spray Tooling process is being adopted at CAD-P lab, ME Department, IIT Kanpur.

4.5 METAL SPRAY TECHNOLOGY

4.5.1 Principle of Electric-Arc Metal Spraying

In electric arc metal spraying, the material is melted and discharged in a very hot state by a special pistol. The procedure is similar to paint spraying. The molten metal is atomized into fine particles by the air system at a temperature of over 2000 °C Striking on the model, which is placed about 20 cm away, the air-molten-metal-stream cools to about 60 °C. On impact, the round particles form a fluid film. Subsequent droplets following the same path, melt together to create a uniform, immediately solidifying surface. If the droplets have cooled so much that they are already solid when they hit the model, they no longer deform and melt into one another, but only come into point contact with neighboring particles. If this happens, an inhomogeneous layer with air inclusions is obtained. On the other hand if the metal is too hot, a molten mass forms on the surface of the model, and is displaced by the air stream. Both these undesirable effects can be controlled by feed rate of the spraying wire, using the controller built into the pistol, and by the airflow rate. In practice, it is important to work at the correct temperature and to keep the distance between die and model constant (about 10 to 20 cm). It is usually possible to detect spraying faults optically on deposition of sprayed metal.

4.5.2 Alloys

The alloys used have low melting points (manufacturer: MCP Mining and Chemical Products, Geneva/Switzerland). They are composed principally of bismuth, tin and zinc; indium is used to obtain an extremely low melting point. By using one or all of these metals, a large number of variants can be obtained. Typical melting points are 47 °C, 58 °C, 70 °C, 96 °C, 124 °C, and 137 °C.

Most of the alloys used for metal spraying are standardized, and contain bismuth. On solidification bismuth shows a volume increase of some 3.3%. By mixing appropriately with other metals that shrink on solidification alloys are created whose

dimensions do not change on solidification. These alloys are relatively hard metals whose strength increases with age. Because these alloys are stable metals, they offer the advantage that can be repeatedly remelted and used again. They are suitable for normal gravity casting as well as for pressure die-casting and vacuum casting, and they can be sprayed like paints. Their exactness of reproduction is unsurpassed and permits contours of all kinds to be reproduced. Because the discharge temperature is low, models made of wood, plaster, plasticine, or even wax can be used as pattern.

Four alloys having required properties like dimensional stability and ease of use have been employed in practice. They are:

- MCP-150 has melting range from 138 °C to 170 °C, and is employed for making molds for thermoforming and polyurethane.
- MCP-200 melts at 200 °C, and is used predominantly for making injection molds.
- MCP-350 has a melting range from 198 °C to 330 °C, and is used for the arc-spraying process
- MCP-400 with a melting range from 390 °C to 410 °C is also used for arc spraying MCP-400 is suitable for making molds for SMC, elastomer processing, injection molding, and for making foundry patterns.

In the manufacturing of molds, these alloys have a special advantage: because of the small amount of heat involved, no stresses occur in the mold and there is no shrinkage. Consequently, the dimensions of the mold correspond exactly to those of the model.

4.5.3 Metal Spraying

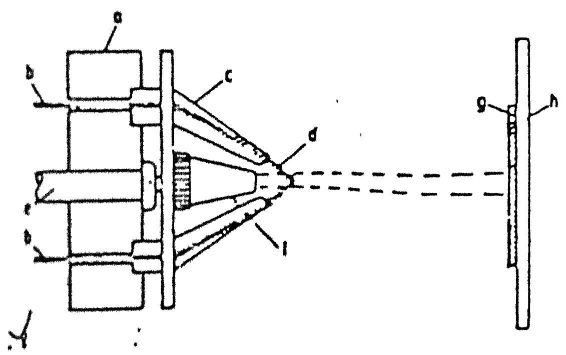


Fig 4.3: Operation of electric-arc metal spraying
a: arc spray gun, b: wire made of a low melting alloy, c: arc, d: jet, e: air house, f: air nozzle, g: coat, h: pattern

There is a distinction between metal spraying at high and at low temperatures. In the first case, the metal is melted in an electric arc (figure4.1), which can melt even molybdenum – melting point of 2620 °C. In the second case, the metal is melted in the spray gun by electric heaters; the highest melting point acceptable here is 200 °C.

In a certain sense, spraying with alloys can be compared to electroforming processes. Electroforming gives the most exact metallic reproduction of surfaces. Here the metal ions are transferred from an anode to a model Although the metal droplets produced in the atomizing nozzle of a spray gun are much larger, the quality of reproduction is nearly as good as with the electrodeposition process. Furthermore, the metal spraying process can be carried out much more rapidly. Investments cost are low, and no special experience is necessary to operate the equipment. In addition, with metal spraying, it is possible to produce molds that are either too big or too costly for the electroforming system. In a process developed in the last few years, electric arc metal spraying, TAFA - the molten metal can be applied in a manner very similar to spraying of paint using a high-velocity air stream. An important condition for this is the setting of specific melting rate. This is accomplished by maintaining the feed rate of the wires constant Another important factor is the distance between their tips, which should also be held constant. An electric voltage is applied between the two wires to produce the arc The temperature of the arc is approx. 4300 °C, but the wire melts with relatively little oxidation, and hardly any heat-transfer to feedstock. All metals – aluminum, copper, zinc, steel, stainless steel, bronze, and molybdenum can be sprayed by this method

4.5.4 Spraying Technique

It is relatively easy to obtain a good quality surface with metal spraying. Successive coats are applied to achieve this. The gun should be moved back and forth across the surface of the model, just fast enough to produce a bright silvery tone overall. The first layer, which will be the inner surface of the mold, is the most important to achieve good particle build-up. It is advisable to start spraying with the smallest metal particle setting. Subsequent layers can be applied faster by use of coarser spray settings.

The layer thickness required for polyurethane models is 1 mm, and for injection tools up to 3 mm. In recesses and cavities, turbulence in the air stream at the surface of the model can give rise to problems. The metal layer at the top edges of recesses builds up, creating a possible danger that the entrance will be closed off before the bottom of the recess is completely filled with metal (figure 4.2).

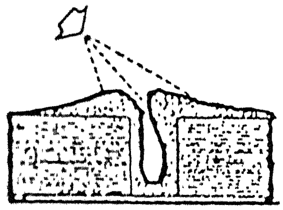


Fig 4.4: Metal-Spraying fault

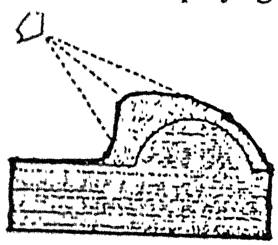


Fig 4.5: One-Side excess deposition of a metal layer during spray

In a similar way, a non-uniform layer can be created over the actual area at which the spray gun is directed. In this case, the operator has sprayed for too long in one direction The metal shell built up in the shadow of the sprayed edge can exhibit a fissured surface.

In order to avoid this, the model should be rotated and the gun as far as possible be directed at right angles to the surface of the model. When spraying larger, particularly shell like models, metal dust can settle on surfaces that are well away from the actual surface being sprayed. It is therefore advisable to use a spray booth with an exhaust system, thus providing a clean atmosphere and working area for the operator.

4.6 MOLD WITH MCP-TAFA METAL ARC SPRAY SYSTEM

4.6.1 MCP-TAFA Arc Spray Process

4.6.1.1 Preparation

Step 1. Preparation of master pattern. Patterns could be of wood, metal or could be a RP component also. In the present work, RP patterns made by FDM-1650 RP machine, available at CAD-P lab, ME department, IIT Kanpur, are used.

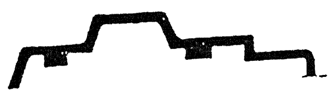


Fig 4.6: Master Pattern

Step 2. The component should be inspected for parting line, orientation, draft, need of cores and inserts etc.

Step 3. A base preferably in wood has to be prepared to orient the component in required fashion. Even though literature says, the base could be of plasticine, plaster of Paris, molding sand and similar things, but only wood is found to perform well. This is due to the reason that during the arc spray, because of heavy air pressure and its high velocity, the base (parting surface)gets deformed which results in defective molds.

Step 4. As per the design, a molding box has to be prepared which could be in wood or perspex sheets or even in metal.

Step 5. Master pattern has to be firmly attached to the base in proper orientation with the help of align pins. Also some dowel pins may be needed to align two molds together.

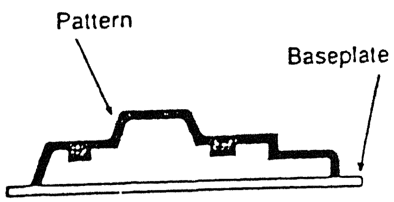


Fig 4.7: Master Pattern in proper orientation

4.6.1.2 Application of Release Agents

Purpose

The master pattern is coated with release agents to anchor the initial spray coat, provide adequate temperature resistance and enable good detail besides facilitating separation of the metal shell from the model. They play a vital role in porous patterns like a FDM component.

Procedure

Step 1. Parting surface should be cleaned out of dust, moisture and any traces of oil or grease.

Step 2. A thin layer of MCP/TAFA pattern sealer wax is applied with a brush on the component and parting surface. After twenty minutes, a second coat is given. Care should be taken to avoid accumulation of wax at some point. The layer should be as thin as possible. Because thicker coat forms a film and affects feature replication during metal spraying.

Step 3. After the wax gets dried, a thin layer of pattern release paint HEK-4140 black spray is sprayed from a distance of 20 to 30 cm onto the pattern. All bottles have to be shaken before use. Due attention should be paid to ensure that spray reaches at all corners and it should be uniform.

Step 4. After black spray gets dried, the last coating of release agent fluid, which is green in color, should be given. This is done with the help of spray gun employing 0.5-mm nozzle.

Within 30 minutes after this green spray, the metal spraying should be started. If needed, the pattern could be kept with black coat for long time, but not with green!

All spray liquids are hazardous to health. All are highly inflammable. So they should be preserved in safe place. They should be kept away from sources of ignition. Inhalation can be lethal.

4.6.1.3 Metal Spraying

Metals with a low melting point are normally used for this purpose. TAFA uses an alloy called 'Kirksite' whose melting point is 400 °C. The metal is supplied in the form of a wire spool. In a specially designed spray gun two such metallic wires are fed and are brought close to each other. A potential barrier enough to break that gap is applied in between them. This produces an arc and melts the metal. The compressed air supplied atomizes the metal and carries it to parting surface. TAFA system is essentially a cold spray process. At the substrate the temperature will hardly exceed 80 °C, provided the minimum specified distance (30-cm) is maintained.

TAFA Cold Arc Spray Procedure

Step 1. The base coated with release agents is kept into the spray booth.

Step 2. Spray booth motors are started and the amount of water flow is adjusted to the required value.

Step 3. Power and air supply to TAFA, power supply unit is ensured to be intact.

Step 4. In the 'Spray Air Only' mode, gun air pressure is set at 80 psi, with first detent on the gun. The voltage is set according to the wire used. For MCP 400, open circuit voltage of 27 is found to be better; because using excessive voltage yields larger particles and poor spray pattern, whereas too low voltage will cause popping.

Step 5. In the spray mode, with second detent on the gun wire feed knob is adjusted to set to 50 Amps.

Step 6. The above settings provide a finer, continuous coating Initially finer spray is done for few layers to ensure feature duplication.

Step 7. Important things to be observed while coating:

- The gun must travel uniformly on all sides.
- The distance from the job should be kept constant (20 to 30 mm).
- Precautions should be taken to avoid component overheating.

Step 8. After few layers, pressures are reduced and wire feed increased to give a coarse, faster coating. With this again uniform spray is done throughout the entire job up to a thickness of 1 to 2mm (uniform) [MCP98].

4.6.2 Casting Process

The casting procedure differs from resin to resin. Hence it is not possible to give exact procedure which is common to all resins that could be used for tooling. In the present work EP-180 epoxy resin, supplied by HEK GmbH is used for all purposes. So the details below will hold well strictly only for this resin. Nevertheless, the overall procedure will be same for a typical epoxy tooling.

Step 1. The sprayed pattern is boxed with metal or wood. Holes, if any should be sealed. If heating or cooling lines are used, the lines should not be suspended less than 25 mm from the pattern surface and should be spaced 50 to 75 mm apart.

Step 2. EP-180 is relatively thick. To reduce the viscosity, it could be pre-heated

Step 3. Hardener Selection

Choice of hardeners for EP-180 resin is done on the basis of tool thickness. Following is a list of the same.

- Hardener EPH-F for tools up to 100 mm thick.
- Hardener EPH-M for tools up to 200 mm thick.
- Hardener EPH-S for tools up to 500 mm thick.

Step 4. Volume Calculations

Deciding the ratio of resin to filler material requires lot of considerations like the kind of resin as well as filler being used, end application of the tool, processability etc. For example, with EP-180, it is strongly recommended to use resin and aluminum granule in equal ratio by weight. Total specific weight of this mixture is 2.5. The amount of hardener used and its selection is based on tool thickness needed. For instance, mixing ratio of EPH-M hardener to EP-180 is as follows:

5 parts of EPH-M to 100 parts of EP-180 without aluminum granules.

An illustrative table is given.

Batch Weight	EP-180 resin	EPH-M Hardener	Aluminum Granules
1 Kg	500 g	25 g	500 g
5 Kg	2.50 Kg	125 g	2.50 Kg
100 Kg	50 Kg	2500 g	50 Kg

Table 4.1 Ratio of resin, hardener, and filler material

Step 5. After pouring hardener to resin, mixing is done for 4 to 5 minutes. For this, a heavy-duty electric drill with low RPM is prescribed.

Step 6. A thin coat of this catalyzed resin is applied with brush on the parting surface as well as on the component.

Step 7. Right amount of aluminum granules is added to the catalyzed resin and

Step 8. The resin aluminum mixture is poured from the deepest point, making sure that the resin leaves no voids around the cooling lines if any.

Step 9. Room temperature hardening is carried out for 12 hours.

In order to complete the polymerization and to stop all reactions, to attain stability and for many more reasons post curing is indispensable. Eventually it depends on the hardener used.

EPH - F and EPH – M	EPH – S
2 hours at 45 C 6-8 hours at 65 C	2 hours at 45 C 4 hours at 65 C 4 hours at 95 C or overnight

Table 4.2 Post curing details

The best method of curing is to use the "cooling lines" with either hot water or oil to heat from the inside to the outside. After this mold should be cooled to room temperature in ambient conditions.

Step 10. After tumbling the first mold half, same procedure should be adopted to get the next half.

The whole process and some examples are depicted in the next page

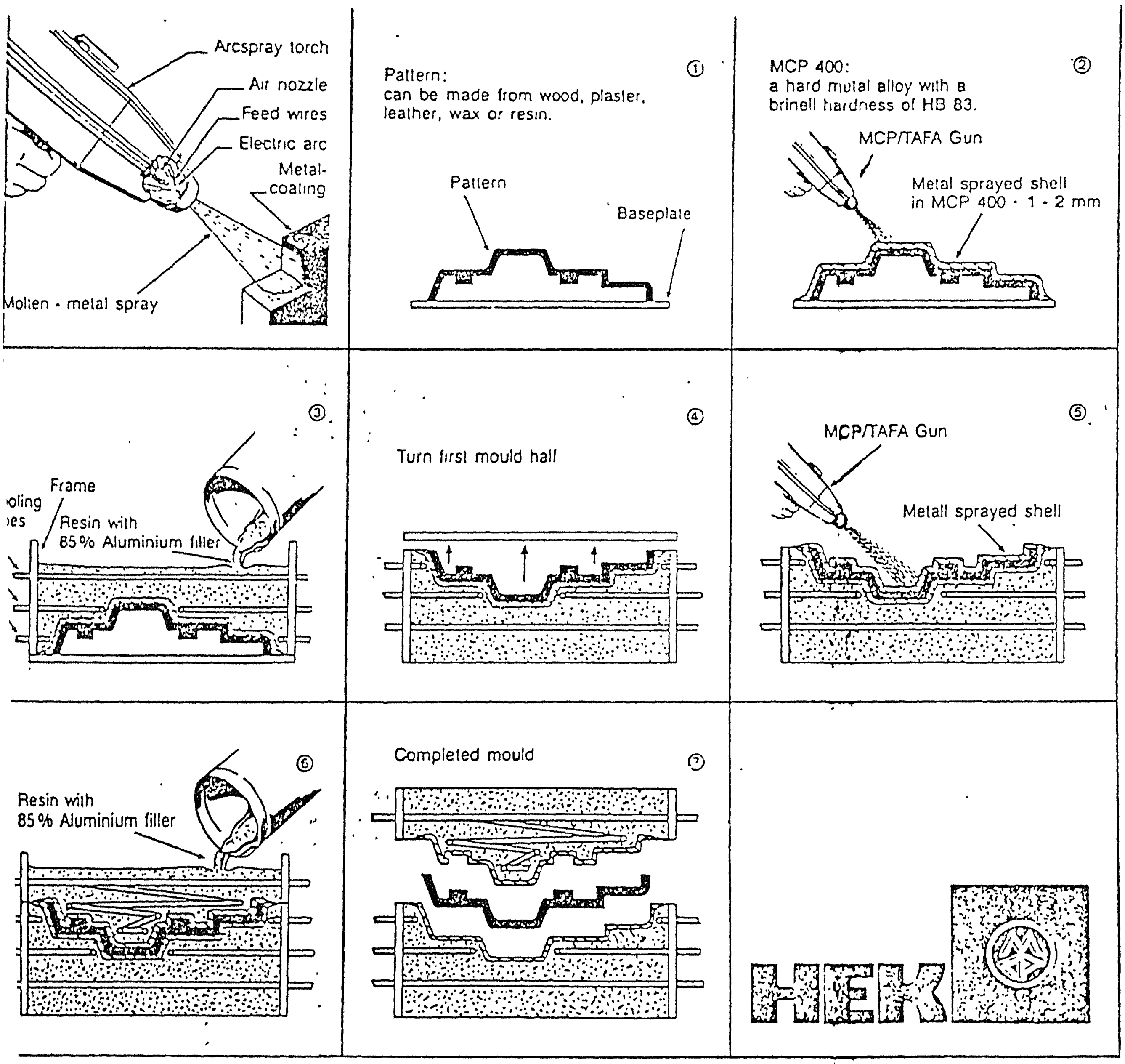


Fig 4.8: Process for making a RIM mold

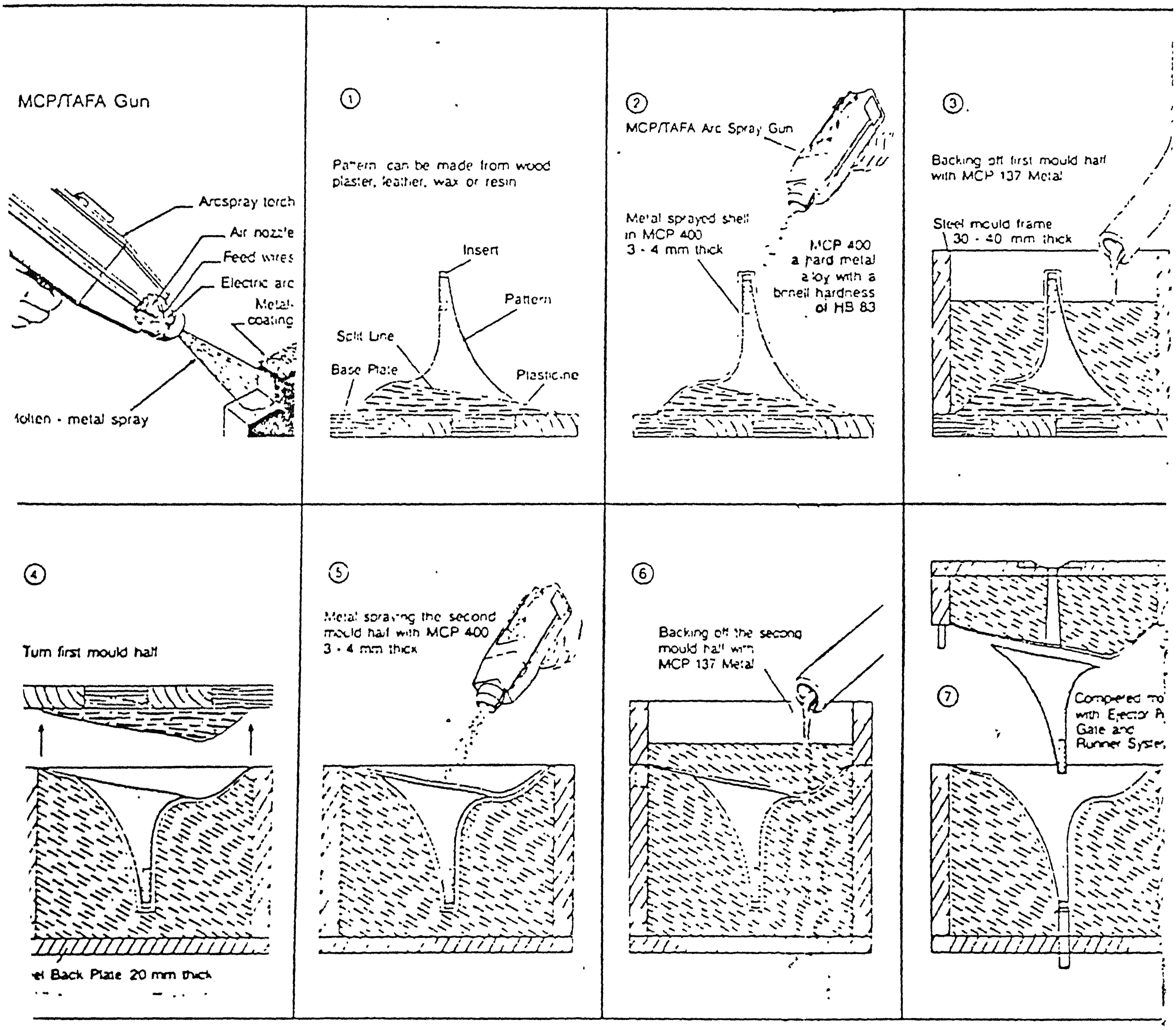


Fig 4.9: Process for making a mold with the MCP/TAFA for injection molding

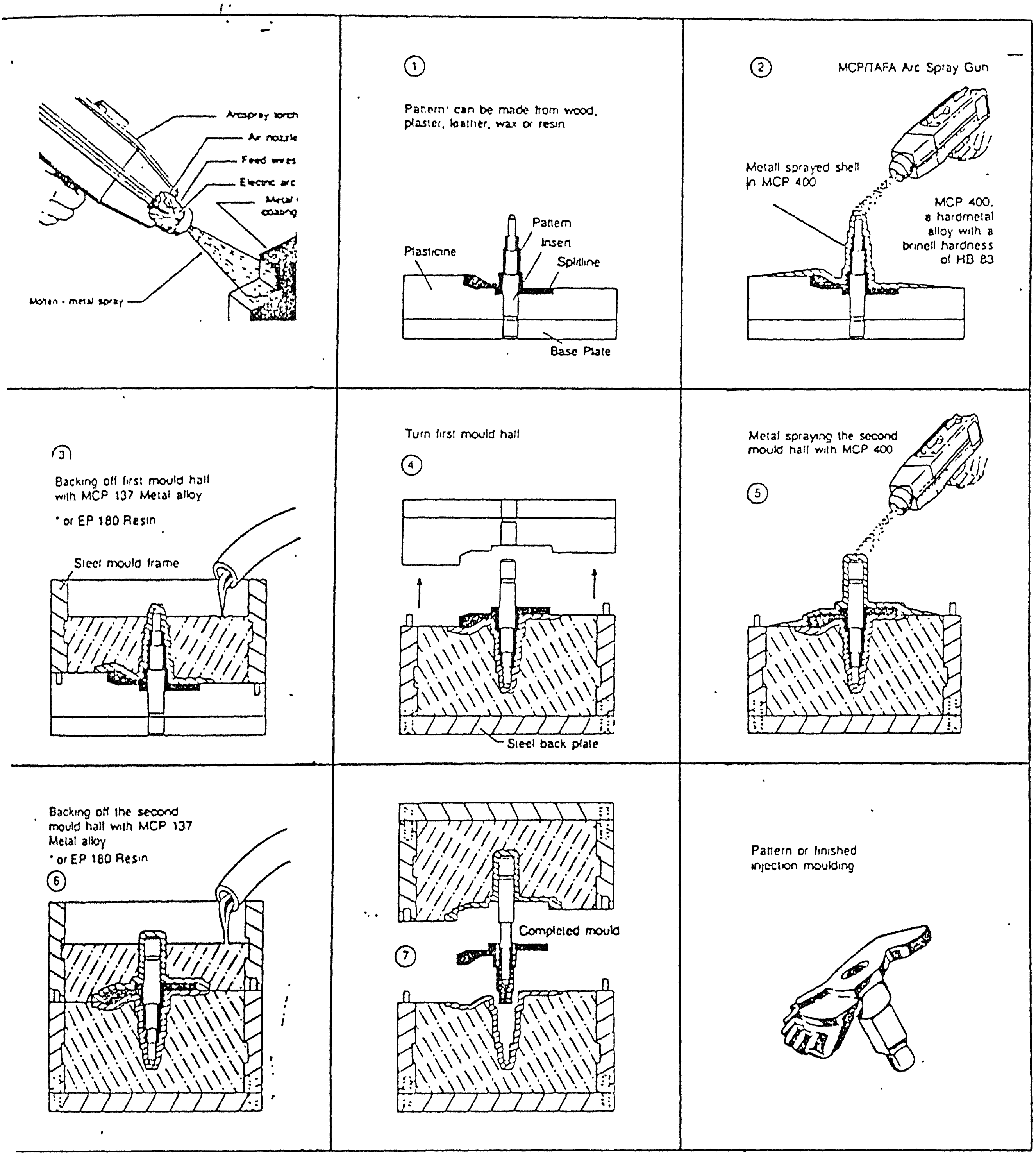


Fig 4.10: Process for making a mold for compact injection mould

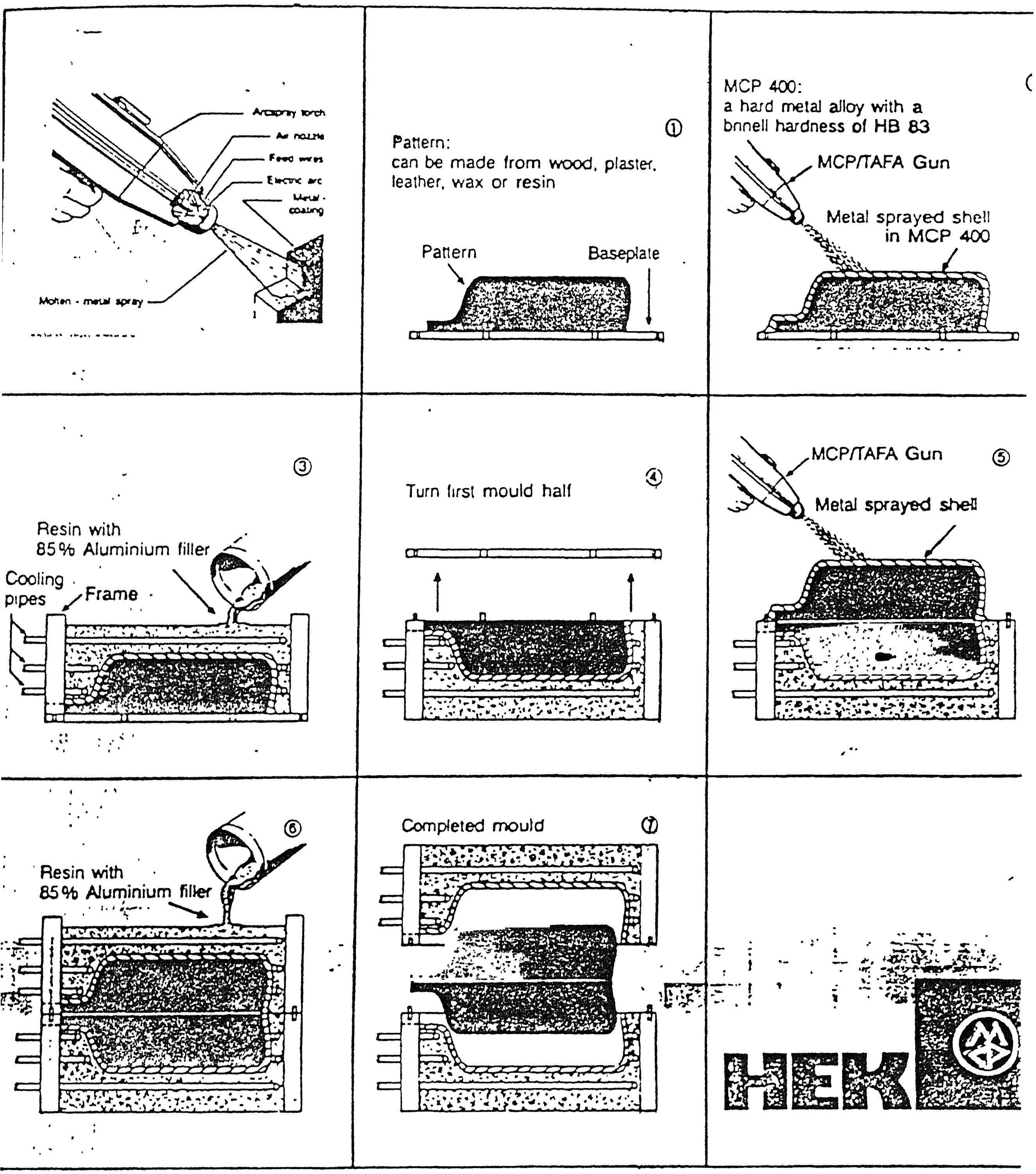


Fig 4.11: Process fo[illegible] MCP/TAFA

Chapter 5
CONCLUSIONS

5.1 COMMENTS ON RESULTS

The results show that the gunmetal gives the least deflection under permissible stress limit. But as compared to gunmetal, RT molds shows reasonably acceptable results in respect of deflection and maximum principal stress. The results show that inclusion increases the strength of the mold appreciably. It decreases the deflection as well as stress induced. In addition to this, steel fillers give better results than aluminum fillers. It has been found that aluminum filler contributes much to thermal properties whereas steel contributes to the strength. By looking at the results, any one might get tempted to make tools with maximum possible amount of inclusions. But it is quite inevitable that as the percentage of inclusion increases, processing becomes more and more difficult, especially in case of small, intricate shapes. Because, in these cases, inclusion might obstruct feature replication. So, there is a compromise between ease of processing and strength.

The molds with metallic coating also give improved results. The metallic coating on epoxy molds enhances the surface of the epoxy mold by giving it a higher heat resistance. It also provides a better surface than epoxy that will last longer. It does not crack and wrinkle as epoxy surfaces often do over a period of time. Spray improves feature replication. Metal surface can be polished, machined and even plated with nickel or chrome.

5.2 SUGGESTIONS FOR IMPROVEMENT OF METHODOLOGY

- The creation of shoe sole is the first as well as important step of prototyping. So, solid modeling as well as reverse engineering should be more refined for virtual prototyping of shoe sole.
- In the reverse engineering, for more accurate digitization of data cloud, digital camera can be used.

➢ The inclusion increment gives more stable molds but it creates complicacy in creation of molds. So, optimal volume fraction of filler material should be carefully computed.

➢ Application of these molds for real life injection-molding components should be validated.

5.3 SUGGESTIONS FOR FUTURE WORK

➢ RT gives the exact replica of features of the surface. So, surface of the RP pattern should be properly cleaned so as to get a better surface texture It is recommended that the finishing processes prescribed by RP machine manufacturers be adopted.

➢ Thermal analysis and fatigue analysis of the molds will give more accurate results of the process.

➢ At present EP-180 epoxy resin is used for mold making. This is a general-purpose epoxy. Special purpose epoxies like thermally conductive epoxy resin will certainly improve the performance of mold in special applications like RIM. Attempts could be made to make molds with these kind of special resins and the process should be studied.

➢ Time dependant analysis may give better results in the tighter tolerance zone.

➢ Shell mold formation of other MCP materials like MCP-200, 250, 350, 400 etc. or other suitable materials can be tried. Backing material can also be suitably altered.

[Anil98] Anil Kumar M., "Rapid Prototyping, Rapid Tooling and Digital Photoelasticity: An Integrated Approach", M.Tech thesis, IIT Kanpur, 1998.

[Bapat98] Vijay P. Bapat, Karunakaran K.P., & Ravi B., "Rapid prototyping and Tooling, New paradigms in Design and Manufacturing", *Rapid Prototype cell, IIT Mumbai*, 1998.

[Beaman97] Beaman J.J.,et.al., "Solid Freeform Fabrication: A New Direction in Manufacturing", *Kluwer Academic Publishers, London*, 1997.

[Bhatt97] Bhatt A.D., Dhande S.G., & Agrawal Sanat, "Rapid Prototyping and Tooling Technolodies", *Proceedings of National Seminar on Emerging Trends in Design Engineering*, Vol 3, !997, pp 118-136.

[Boender94] Boender E., Brosvoort W.F., & Post F.H., "Finite-element mesh generation from constructive-solid-geometry models", *Computer-Aided Design*, Vol 26, No. 5, May 1994, pp 379-392.

[Deol93] Deol T.J.A., Loretto H.M., & Bowen P., "Mechanical properties of aluminum based particulate metal-matrix composites", *Composites*, Vol. 24, No 3, 1993.

[Dhande98] Dhande S. G., "Rapid Tooling Lecture Notes", *CAD Project, I.I.T. Kanpur*, 1998.

[Dolenc94] Dolenc A., & Makela I., "Slicing procedure for layered manufacturing techniques", *Computer-Aided Design*, Vol 26, No 2, February 1994, pp 119-126.

[Everett78] Everett E. Adam & Ronald J. Ebert, "Production and Operations Management", *Prentice-Hall, Inc., New Jersey*, 1978.

[FDM96] FDM system Documentation by Stratasys Inc., May 1996.

[Floriani85] Floriani L.De, Falcidieno B., & Pienovi C., "Delaunay-based Representation of surfaces defined over arbitrarily shaped domains", *Computer Vision, Graphics, and Image Processing* 32, 1985, pp 127-140.

[I-DEAS] I-DEAS smartview guides.

[Jacob92] Jacob P. F., "Rapid prototyping & manufacturing, Fundamentals of stereolithography", *Society of Manufacturing Engineers, Dedarborn*, 1992.

[Kai96] Kai C.C. & Fai L.K., "Rapid Prototyping – Principal and Applications", Wiley *Eastern, New York*, 1996.

[Kulkarni96] Kulkarni P., & Dutta D., "An accurate slicing procedure for layered manufacturing", *Computer-Aided Design*, Vol 28, No 9, 1996, pp 683-697.

[MCP98] "MCP TAFA Cold Spray Mold Making", *HEK GmbH, Germany*, 1998.

[Mink64] Mink W., "Practical injection Molding of Plastics", *Iliffe Books Ltd., London*, 1964.

[Piegl98] Piegl L.A., & Tiller W., "Geometry-based triangulation of trimmed NURBS surfaces", *Computer-Aided Design*, Vol 30, No. 1, 1998, pp 11-18.

[Pye78] Pye R.G.W., "Injection Mold Design", *George Godwin Pub.*, 1978.

[Rahul99] Rahul Kumar, "Development of rapid prototyping and tooling for composite and sheet metal applications", M.Tech. thesis, IIT Kanpur, 1999.

[Rao94] Rao P.V. Madhusudan, "Virtual and Real Shape Prototyping", CAD Project, IIT Kanpur, 1994.

[Reddy93] Reddy J.N., "An introduction to Finite Element Analysis", *McGraw Hill*, 1993.

[Richard77] Richard B. Chase & Nicholas J. Aquilano, "Production and Operation Management", *Richard D. Irwin Inc., New York*, 1977.

[Richard79] Richard N. Cardozo, "Product Policy", *Addison Wesley, Massachusetts*, 1979.

[Sabourin96] Sabourin E., & Houser S.A., "Adaptive slicing using stepwise uniform refinement", *Rapid Prototyping Journal*, Vol 2, No 4, 1996, pp 20-26.

[Sheng92] Sheng X., Hirsch B.E., "Triangulation of trimmed surfaces in parametric space", *Computer-Aided Design*, Vol 24, No. 8, 1992, pp 437-444.

[Sridharan98] Sridharan V., "Effect of Metal Spray Coating on Epoxy Tooling", M. Tech thesis, IIT Kanpur, 1998.

[TAFA98] "Arc spray application data", by TAFA Inc., Jan. 1998.

[Yan96] Yan X. and Gu P., "Survey-A Review of Rapid Prototyping Technologies and Systems", *Computer-Aided Design*, Vol. 28, No.4, 1996, pp 307-318.

[Zheng96] Zheng Y., Lewis R.W., & Gethin D.T., "Three-dimensional unstructured mesh generation: Part 1. Fundamental aspects of triangulation and point creation", *Computer Methods in Applied Mechanics and Engineering* 134, 1996, pp 249-268.

ANNEXURE 1

SLICING: -

Producing parts by layer-based manufacturing requires the transformation of geometric description of a part into a format suitable for processing of the particular RP process. The process proceeds by first slicing the geometric description of the part into layers representing the build planes, typically at 0.005-0.010 inch interval. The slicing operation generates the curves, or contours, that represent the boundaries of the part for each layer. The contours are then processed in a manner according to the particular RP technology. Slicing consists of computing the intersection of the geometry of the part with a series of planes.

SLICING ALGORITHM: -

A faceted representation of a part, such as the STL format, is by definition an approximation of the surface geometry. The main advantage of this representation is the simplicity of the intersection calculations for slicing such models. Conceptually, the slicing operation consists of computing the intersection of the slicing plane with each of the planar facets, resulting in a set of line segments. The triangular facets used in the STL format simplify the calculations further, since each facet is necessarily convex. Mathematically, determining the intersection of a triangular facet and a slicing plane reduces to computing the intersection of the slicing plane with each of the three line segments that define the triangular facet.

If the coordinates of the facet vertices are denoted (x_i, y_i, z_i, i = 1...3), and the slicing plane is given by $z = z_0$, where z_0 is the height of the slicing plane, then the coordinates of the intersection point are determined by solving the following equations:

$$\frac{z_0 - z_i}{z_{i+1} - z_i} = \frac{x_0 - x_i}{x_{i+1} - x_i} = \frac{y_0 - y_i}{y_{i+1} - y_i}$$

Where (x_0, y_0, z_0) are the coordinates of the intersection point. For non-degenerate triangular facets, there will we two such intersection points for each slicing

plane. These intersection points are then assembled in the proper order to produce the approximate planar contour of the part. Assembly of the final contour is the most complex step of the process, as care must be taken to properly account for multiply connected contours that result from slicing non-convex objects. Also, a robust slicing algorithm must handle the special cases where a vertex, edge, or entire facet lies in the slicing plane.

An another approach to slicing faceted geometries based on topological data structure that removes redundant data present in the input file and represents facet adjacency through a face-edge-vertex structure. The algorithm begins by determining the intersection of the current slicing plane with a given triangular facet. The most common case will result in an intersection with two of the facet's edges and generate one segment of the contour. The next facet to intersect is then chosen based on the adjacency information in the geometric data structure. The contour edge generated by this facet is known to connect to the previous contour edge by virtue of the adjacency of their respective facets. This approach greatly simplifies the process of building the final contours, since the contours are built incrementally as the intersections are computed. The degenerate cases of facet-in-plane, edge-in-plane, and vertex-in-plane are handled separately, and require slightly more complicated decisions. The final step for each layer is determining the correct orientation for each contour. This operation is based on in-plane ray tracing to determine which contours others contain. Orientation is then alternated between CCW and CW, with the outermost contours being oriented CCW.

The slicing operation required for layered-based manufacturing technologies introduces errors in final geometry and surface finish. This is the so-called "stair-case" or "aliasing" effect caused by approximating angled surfaces with stacked layers of material. This source of error is generated by the constant slice thickness assumed by most RP software. Aliasing can be reduced by computing variable or adaptive slice thickness based on, for instance, the curvature of the part's surface. Adaptive slicing results in improved accuracy with fewer total slices, resulting in increased build speed.

ANNEXURE 2

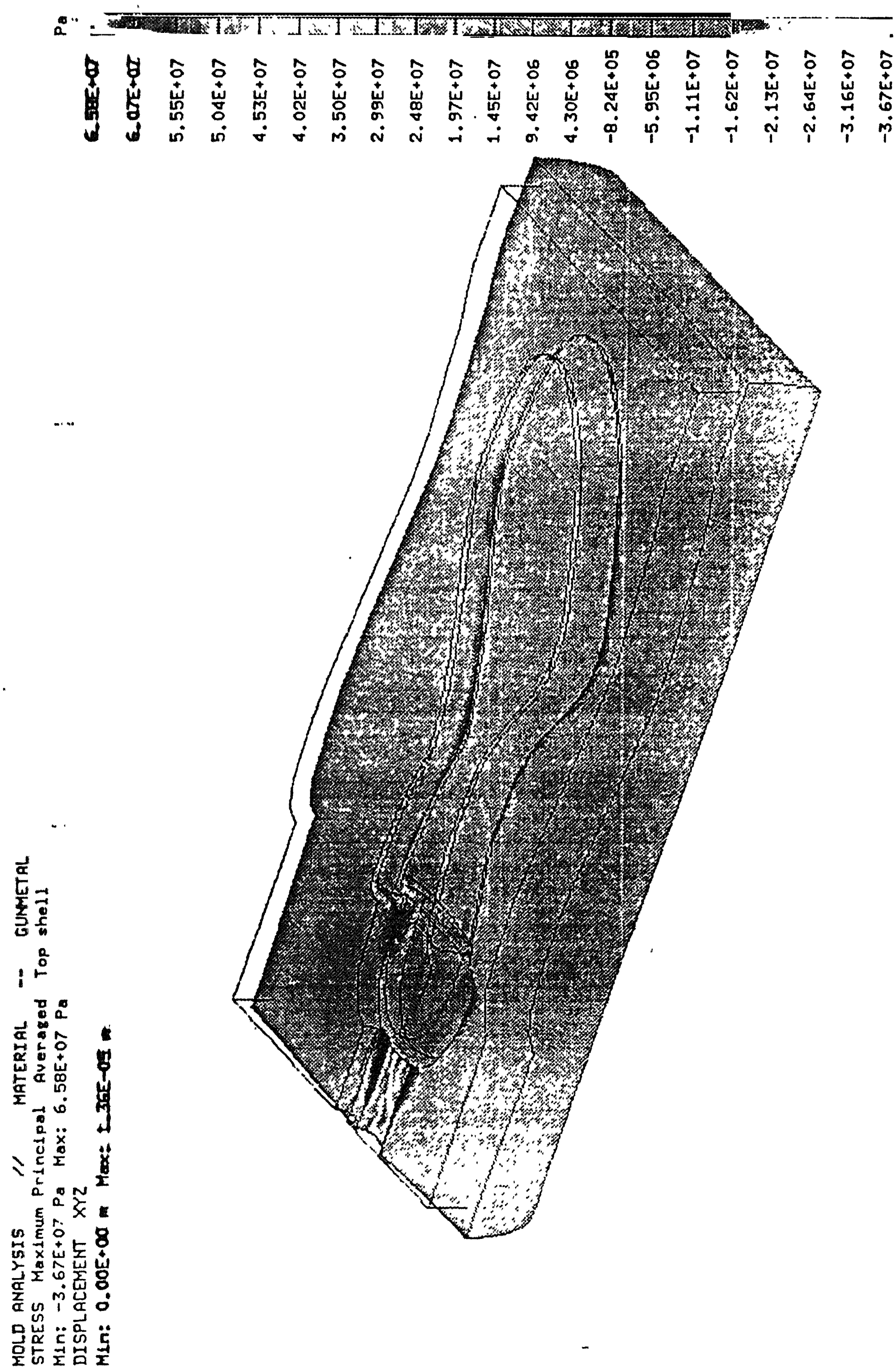


Fig A-2.1: Stress contour plot for Gunmetal alloy mold

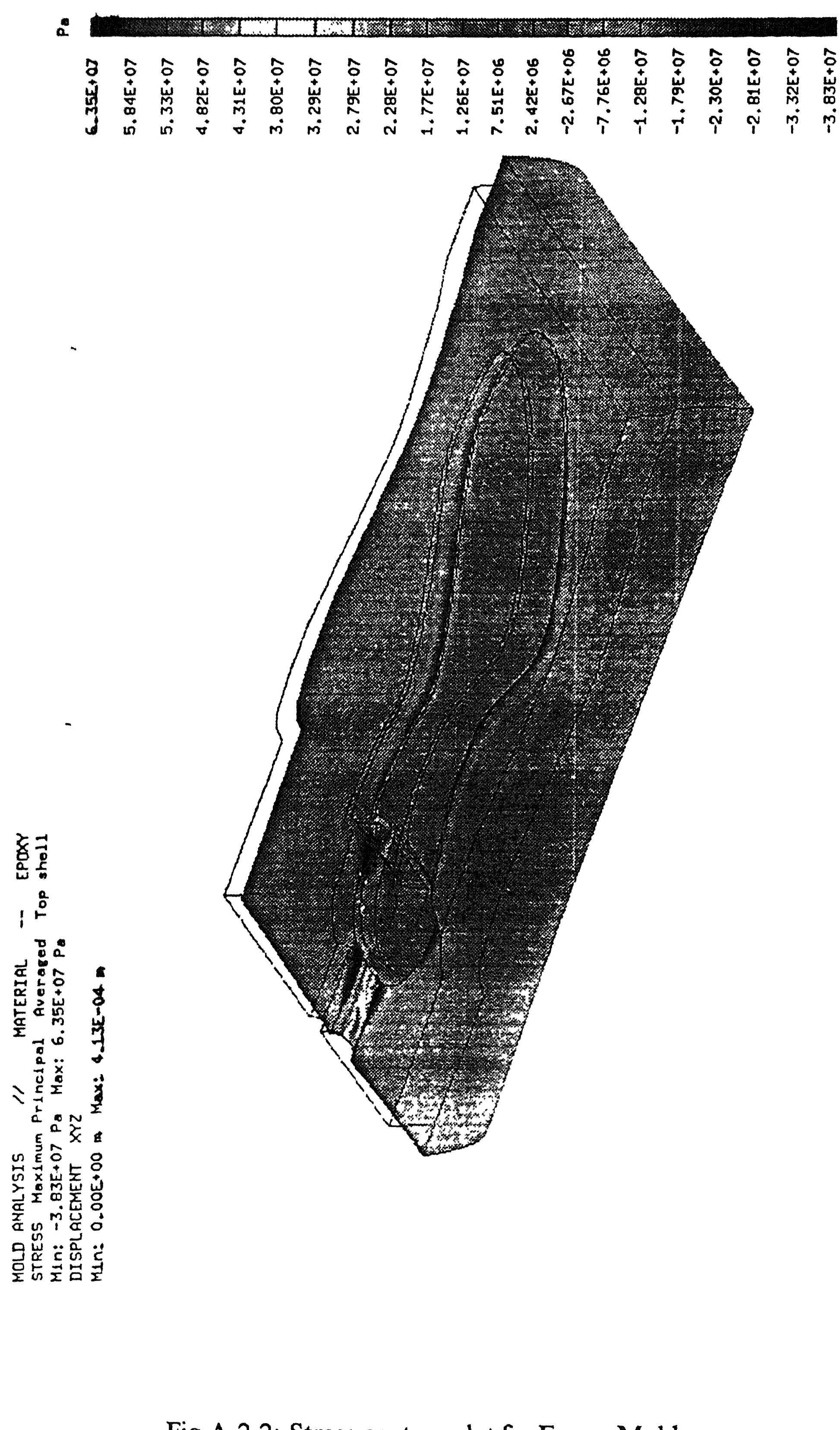


Fig A-2.2: Stress contour plot for Epoxy Mold

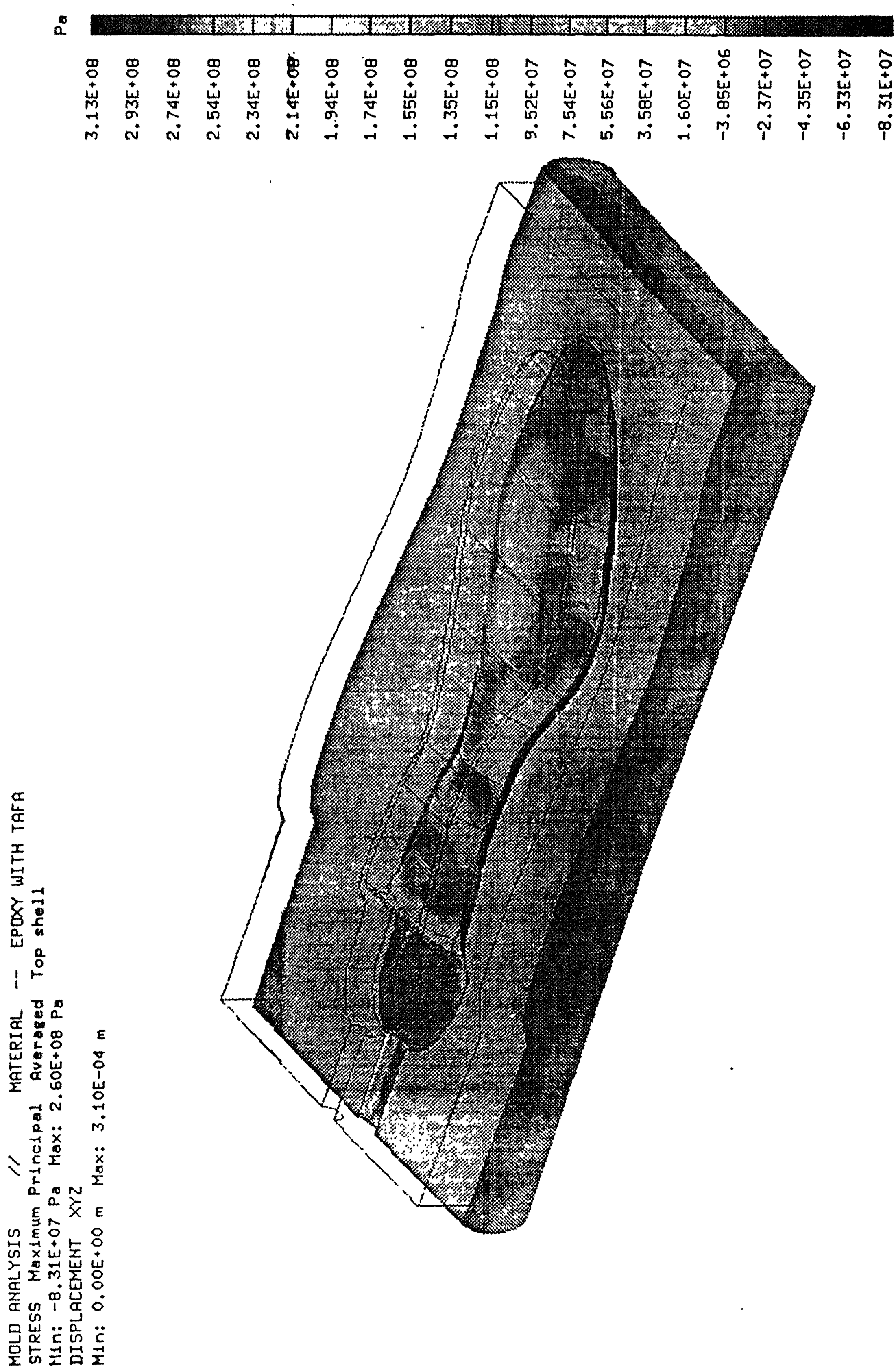


Fig A-2.3: Stress contour plot for Epoxy Mold with metallic spray

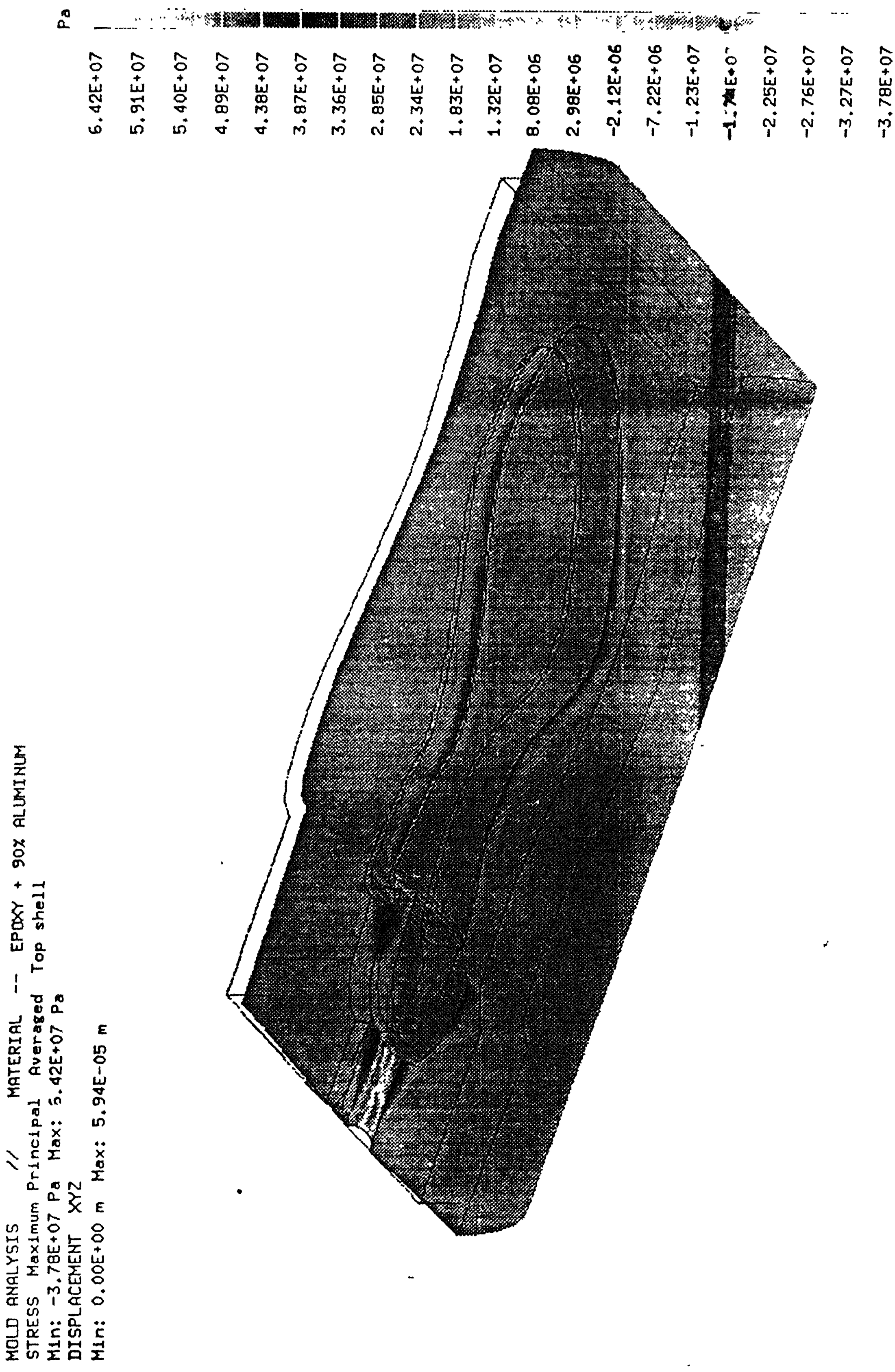


Fig A-2.4: Stress contour plot for Epoxy + 90% Al filler Mold

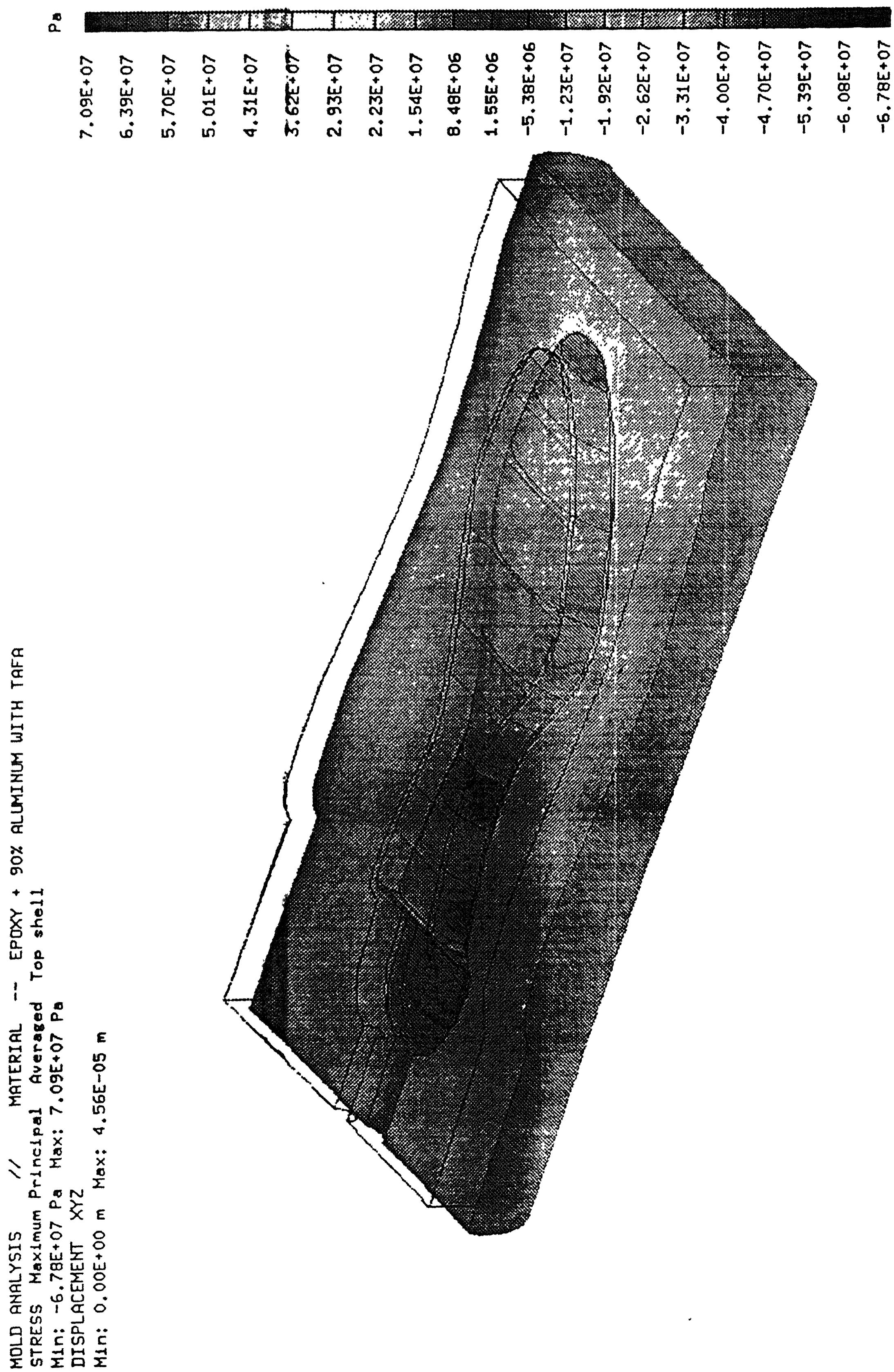


Fig A-2.5: Stress contour plot for Epoxy + 90% Al filler Mold with metallic spray

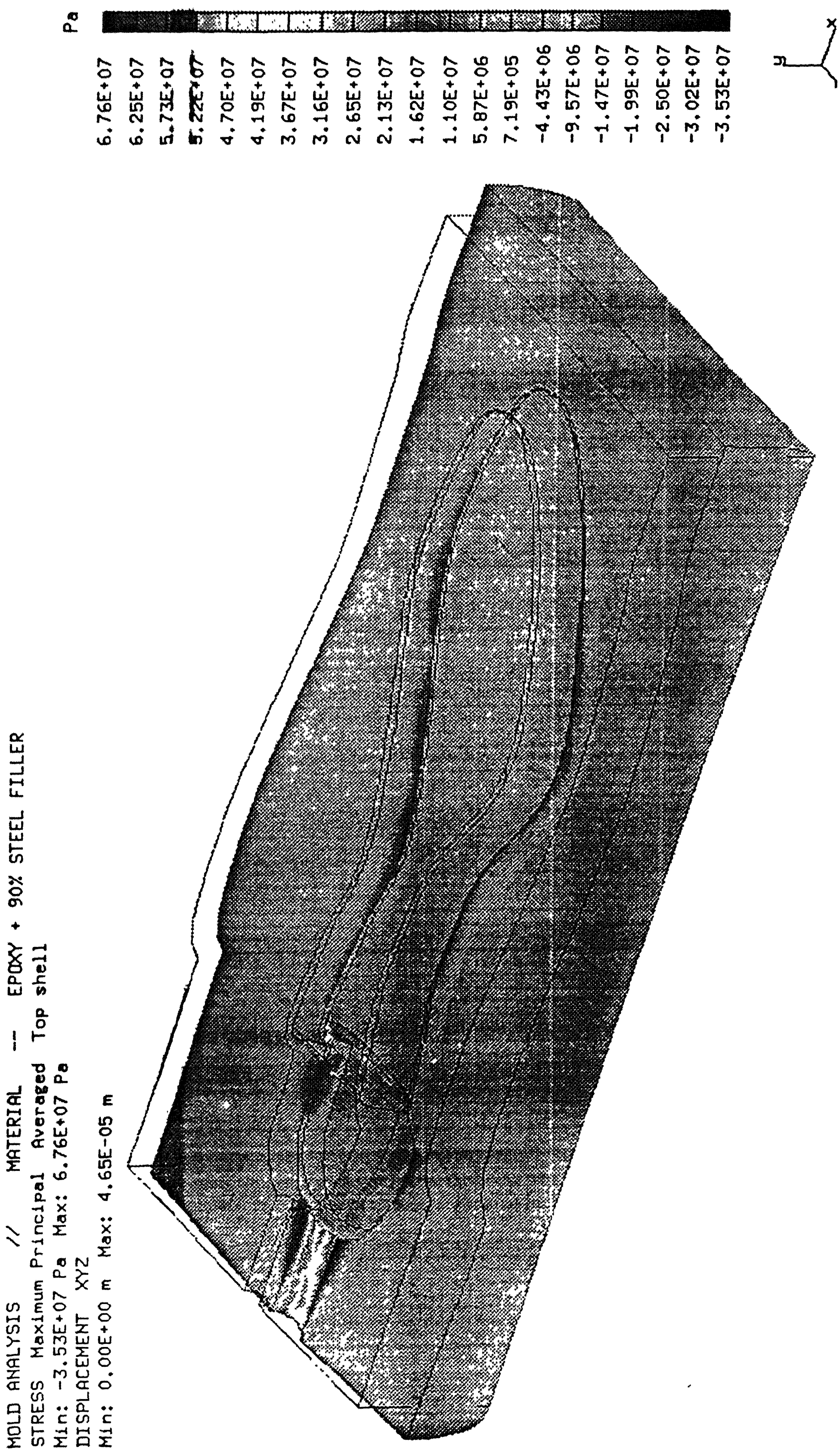


Fig A-2.6: Stress contour plot for Epoxy + 90% Steel Mold

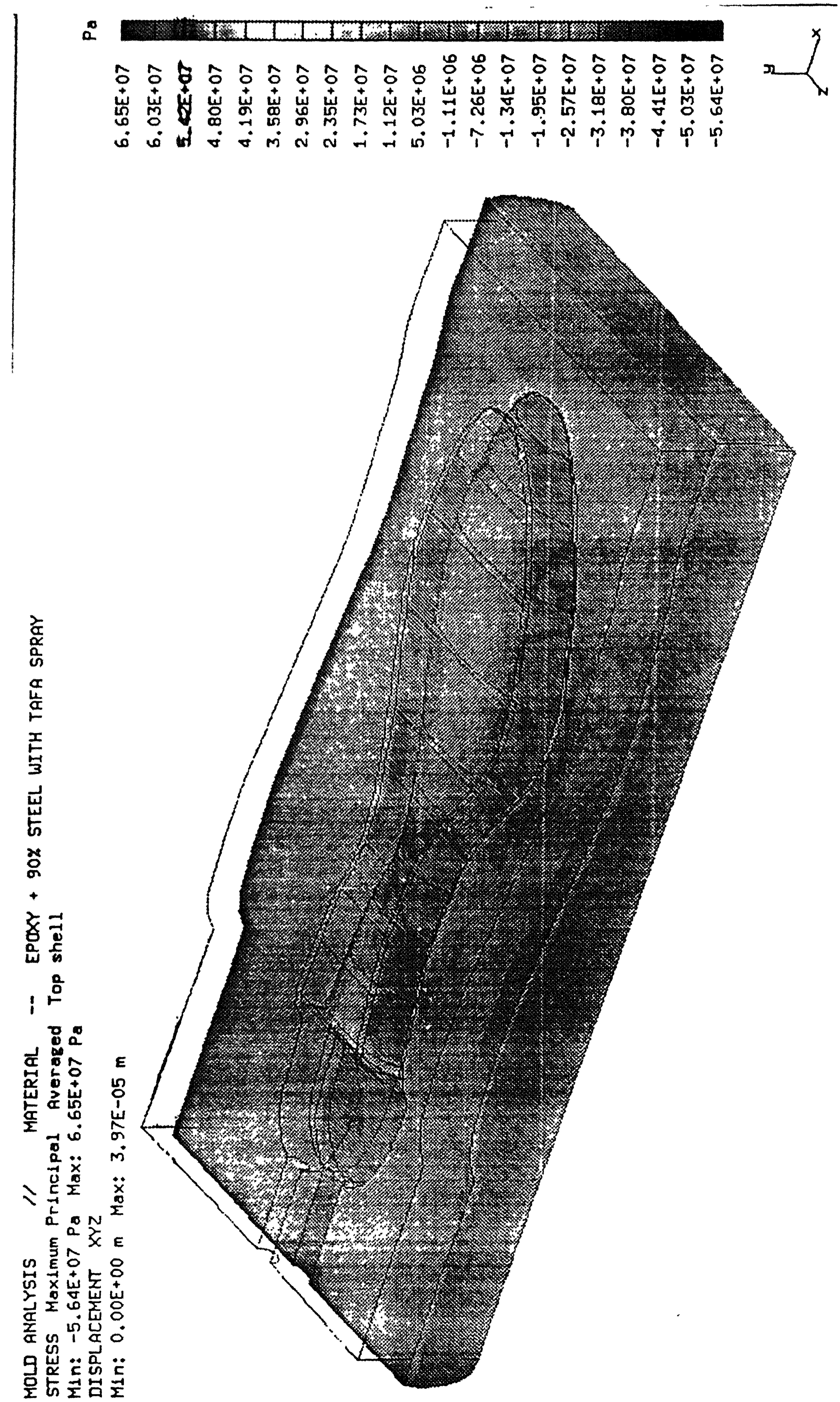


Fig A-2.7: Stress contour plot for Epoxy + 90% Steel Mold with metallic spray